BIOECONOMICS OF INVASIVE SPECIES: THE GYPSY MOTH

by Xi Yang

BIOECONOMICS OF INVASIVE SPECIES: THE GYPSY MOTH

A Dissertation

Presented to the Faculty of the Graduate School

of Cornell University

In Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy

by

Xi Yang

August 2010

BIOECONOMICS OF INVASIVE SPECIES: THE GYPSY MOTH

Xi Yang, Ph. D.

Cornell University 2010

This dissertation studies the bioeconomics and management of an invasive species. It uses gypsy moth as an example to examine the optimal control of invasive species. This dissertation is composed of five chapters. Chapter one provides an overview of the current bioeconomic research and the main questions I want to address in this dissertation. I would like to integrate economic analysis and biological analysis in this dissertation to provide a framework for bioeconomic research. I also want to study the spatial nature of the biological invasion process and design spatial policies to target invasive species. Computational methods are applied to solve resource management problems. Chapter two reviews the history of the gypsy moth invasion and briefly describes the biology of the gypsy moth. Chapter three uses a contingent valuation method to determine the willingness to pay to avoid different defoliation levels. A quadratic damage function is estimated from responses to the willingness to pay survey. Chapter four develops a bioeconomic model to study the optimal threshold policy for controlling an established gypsy moth population. Chapter five uses a diffusion model to study the gypsy moth diffusion process and evaluate the effectiveness of associated policies.

BIOGRAPHICAL SKETCH

Xi Yang was born on September 2, 1979 in Hebei Province, China. She earned her Bachelor's degree in Economics in 2001 from Renmin University of China and Master's degree in Economics in 2004 at the same University. She came to Cornell University in the fall of 2004 for her Ph.D. study in the field of Applied Economics and Management. During her study at Cornell University, she developed her research interest in resource and environmental economics.

To my family

ACKNOWLEDGMENTS

I would like to thank all those people who made this dissertation possible. First of all, I am deeply indebted to my major advisor, Professor Jon Conrad, who provides me with tremendous support, academically mentally and financially during my Ph.D. studies at Cornell University. I would like to thank my committee members, Professor Ravi Kanbur, Professor Nancy Chau for their kind help and guidance in my dissertation research. I am also grateful to Professor Ann Hajek and Andrew Liebhold for their feedback on the design of survey questionnaire and early draft of my work.

I would like to thank the Department of Applied Economic and Management and National Science Foundation for providing the fellowship and assistantship that made this dissertation possible.

I would like to thank my mother and father for their love and encouragement, thank my husband Mao for his support and patience and thank my daughter Cornelia for all the pleasures she brings to my life.

TABLE OF CONTENTS

Biographical Sketch…………………………………………………………….….iii

Dedication……………………………………………………………………….…iv

Acknowledgements…………………………………………………………….....v

Table of Contents………………………………………………………………..vi

List of Figures……………………………………………………………..…viii

List of Tables……………………………………………………………….......ix

CHAPTER 1 Introduction and Overview…………………….………….....................1

References..……………………………………………………………….....6

CHAPTER 2 History and Biology………………………………………….….............8

2.1 History of gypsy moth invasion…………..…………………………….......8

2.2 Biology of gypsy moth…..11

2.2.1 Life Cycle……………………………………………….....11

2.2.2 Host………………………………………………………..12

2.2.3 Population Dynamics……………………………………...13

2.2.4 Natural Enemies…………………………………………...15

2.2.5 Dispersal…………………………………………………..16

References……………………………………………………………......18

CHAPTER 3 Willingness to Pay……………….…………………….....................20

3.1 Introduction………………………………………………………….20

3.2 Literature Review………………………………………………….....21

3.3 Contingent Valuation Survey…………………………………….….23

3.3.1 Survey Instrument…………………………………………23

3.3.2 Estimation Framework…………………………………….32

3.4 Results……………………………………………………………….33

3.5 Conclusions……………………………………………………………41
References……………………………………………………………….43
CHAPTER 4 Population Dynamics Model......……………………………………… 45
4.1 Introduction and Literature Review………………………………………45
4.2 Bioeconomic Model……………………………………………………48
4.3 Results…………………………………………………………….…56
4.4 Discussions and Conclusions……………………………………..…62
References……………………………………………………………….66
CHAPTER 5 Diffusion Model………………………..……………………………68
5.1 Introduction and Diffusion Model Review………………………………..68
5.2 Spatial Dynamic Model…………………………………………………...73
5.2.1 Biological Model……………………………………..……75
5.2.2 Economic Model……………………………………...…76
5.2.3 Optimization Problem……………………………………...78
5.3 Results……………………………………………………………......80
5.4 Conclusions…………………………………………………….........84
References………………………………………………………………..86
APPENDIX………………...………………………………………………………….89

LIST OF FIGURES

FIGURE 2.1 The Spread of Gypsy Moth……………………………………………10

FIGURE 2.2 Defoliation in Northeastern U.S (1924-2009)…………………………14

FIGURE 3.1 The Study Area………………………………………………………27

FIGURE 3.2 Damage Function……………………………………………………40

FIGURE 4.1 The Phase-Plane for Equations (4.1´) – (4.4´) with $\sigma^2 = 0$ ……...…...52

FIGURE 4.2 The Phase-Plane for Equations (4.1´) – (4.4´) with $\sigma^2 = 0.09$ …...…..53

FIGURE 4.3 Coarse-Grid Search for X^* when $\sigma^2 = 0$ …………………………...58

FIGURE 4.4 Fine-Grid Search for X^* when $\sigma^2 = 0$ ……………………….......59

FIGURE 5.1 Gypsy Moth Spread Simulation (No Control)…………………………81

FIGURE 5.2 Gypsy Moth Spread Simulation (Spray Policy)………………………..82

FIGURE 5.3 Gypsy Moth Spread Simulation (Quarantine Policy)..…………………83

FIGURE A.1 The Dynamics of N-I-Z system for the First Fifty Years……………...91

LIST OF TABLES

TABLE 3.1 Geographical Distribution of the Responses..…………………………...26

TABLE 3.2 Definition of Variables………………………………………………..28

TABLE 3.3 Summary Statistics for Bid and Response……………………………....31

TABLE 3.4 Determination of WTP for 10% Defoliation…………………………….34

TABLE 3.5 Determination of WTP for 20% Defoliation…………………………….35

TABLE 3.6 Determination of WTP for 30% Defoliation…………………………….36

TABLE 3.7 Determination of WTP for 40% Defoliation…………………………….37

TABLE 3.8 Estimation of WTP………………………………………………………39

TABLE 3.9 Estimation of Total WTP………………………………………………..41

TABLE 4.1 Parameters Used in the Bioeconomic Model……..……………………..57

TABLE 4.2 Optimal Thresholds and Present Values for Different σ ………………60

TABLE 4.3 Comparative Statics of X^* and D^* when $\sigma = 0.3$…………………61

TABLE 5.1 Parameters Used in the Model………………………………………..80

TABLE 5.2 Summary Statistics for Different Control Scenarios …………………....83

TABLE A.1 Suppression Cost Summary Statistics…………………………………..89

TABLE A.2 Calculation of Damage Function………………………………………..90

CHAPTER 1

INTRODUCTION AND OVERVIEW

Invasive species are non-native organisms that can cause damage to environments, economies and human health. Invasive species are an important cause of ecological change. According to Cox (1993), there are 256 vertebrate extinctions with an identifiable cause, and 109 of them are known to be due to biological invaders.

There is a large literature in biology which studies invasive species extensively in a wide variety of ecosystems, terrestrial, fresh-water and marine, animal, plant and microbe. This literature provides a solid foundation for understanding invasive species, but the problem is not only a biological problem. The introduction of invasive species is accelerated by domestic as well as international trade. The spread of invasive species is largely human-mediated. Economics can play a key role in the management or control of an invasive species. Optimal control requires an evaluation of economic damage, the cost of prevention and control, and models to describe the dynamics.

Invasive species cause significant economic damages. Pimentel et al. (2000) estimated that the total environmental damages and losses of all invasive species in United States is $137 billion per year. Even this number is considered an underestimate of total economic damage because a lot of factors are simply not taken into consideration, for example species extinction, and the loss in biodiversity, ecosystem services, and aesthetics.

Prior to Clark's book *Mathematical Bioeconomics* (1990), the literature from biology and economics are largely isolated from each other. Biological studies often do not consider the human impacts when the model of population dynamics is designed. Economists use highly simplified biological models to capture the population dynamics of invasive species, which makes the study unrealistic. In the context of resource economics, more realistic models are required to inform policy. So a lot of work is needed to compensate this gap. In this paper, we will build a bioeconomic framework for the management and evaluation of invasive species.

The issues I wish to address in this dissertation are three in number.

First, I would like to explore the way to integrate biology into economics so that we can design better invasive species management policies. Integrating ecological and economic analysis is essential to guide policy development in support of more cost-effective management. (Keller et al. 2009) In the real world, economic system and ecosystem interact with each other. Ecosystem respond to human behavior and human also adapt to the change of environment. For the invasive species problem, human trade, transportation and travel behaviors promote the introduction and spread of invasive species. Human also need to adapt to and reduce the impact caused by the invasive species. If we analyze an invasive species and its environment as a dynamic system, we can take such interactions into consideration.

The main questions we want to explore in this part are: how we can design a framework to integrate biology and economics and to determine what net gains can be achieved by doing so.

There are some pioneering works in this line of research. For example, Shogren (2000) uses an endogenous framework to analyze the risk posed by invasive species. This paper studies how a benevolent manager allocates scarce resources to maximize expected social welfare subject to the risk of invasion. The manager chooses prevention and control efforts to maximize expected social welfare. The probability structure is determined by the biological system and human behaviors (mitigation efforts). The social value of different states of nature is also a function of biological factors and people’s behavior (mitigation and adaptation activities). A necessary condition for a manager’s optimal levels of mitigation and adaptation requires equalization of the expected marginal returns on investments in mitigation and adaptation. This model allows economists to frame the invasive species problem in cost-benefit terms. Saphores and Shogren (2005) use a real-option framework in continuous time to study when to control an invasive species. This paper solves for an action rule that triggers the control of an invasive species. This paper also captures two important features (uncertainty and irreversibility) in the invasive species management.

Population density is generally assumed to be an exogenous random process. In chapter 4, I also investigate the interaction of an invasive species and its environment, including a pathogen and a predator. In this dissertation, I would like to employ a stochastic dynamic optimization framework to study the control of an invasive species. The resource manager chooses the optimal control strategy from a variety of control options to minimize the discounted sum of damage and control cost.

Second, I would like to study the spatial nature of the biological invasion process and design spatial policies to target invasive species. In chapter 5, I investigate how to allocate resources spatially to optimally control the spread of invasive species. With a few notable exceptions, spatial interconnections and heterogeneity in resource management are largely ignored in the current bioeconomic literature. For many resources management problems spatial dynamics are essential. For an invasive species, the control decision in one area will affect the spread and hence the control decisions in all other areas. An interesting question here is where and when to initiate control. Because of the heterogeneity of resources and mobility and heterogeneity of economic agents, it is unlikely that a single resource management policy will be effective everywhere. In this dissertation, I take advantage of spatial time-series data and use spatial estimation and simulation to investigate the optimal way to allocate management efforts over time and space.

Some pioneering work in the spatial-dynamic resource economics includes:

Sanchirico and Wilen (1999, 2005), Smith et al. (2009), and Brock and Xepapadeas (2008). In all of these papers, the decision variable is harvest effort and the decision space is continuous. Most of the literature concentrates on the fishing industry. A few papers discuss the biological invasion problem in depth. Economists have largely ignored the spatial-dynamic aspects of bio-invasions, often treating them as a pest-control problem. This misses the most interesting aspects of bio-invasions, namely their spatial-dynamic character. (Wilen 2007) In chapter 5, I use a spatial-dynamic framework to study a biological invasion problem.

Many bioeconomic problems, including invasive species management, have important spatial-dynamic aspects. Control and state variables have both a temporal and spatial dimension. Control efforts must specify not only how much to spend and also where to spend. Spatial-economic analysis has greatly benefited from the advancement in GIS modeling and spatial analysis has seen resurgence. We can also use spatial economic analysis in resource economics.

Third, I apply computational methods to resource management problems. The invasive species management problem is a computationally intensive or computationally hard problem because it involves the interaction of invasive species, humans and quite often other (nonhuman) species. In order to solve a set of problems like this, we need to employ computational methods.

The challenge of integrating biological and economic analysis is the complexity of the model. The spatial problem is a NP hard question, we need to use computational methods to transfer it into a question solvable in polynomial time.

In this dissertation, I use the gypsy moth as an example of an invasive species and examine the bioeconomics of the gypsy moth in the northeastern United States. The gypsy moth was introduced to United States in 1869. The range of gypsy moth has spread to include most of the northeastern states in the US. The gypsy moth has become a major pest of US forest and ornamental trees, especially oaks (Campbell and Schlarbaum 1994). Because of the long history of introduction and data availability, the gypsy moth is a perfect example for us to study population dynamics and the interactions between an invasive species and humans.

The remainder of this dissertation is organized as follows. This introduction and overview is followed by a brief history of gypsy moth and its biological characteristics. Chapter 3 estimates willingness to pay to avoid different degrees of defoliation. I also identified key determinants of willingness to pay for different defoliation levels. In Chapter 4, I developed a bioeconomic model to study the optimal control of an established gypsy moth population. In chapter 5, reaction diffusion models are used to analyze the spatial-dynamics of the gypsy moth and to calibrate the model using historical data.

REFERENCES

[1] Brock, W. and Xepapadeas, A. 2008 Diffusion-induced instability and pattern formation in infinite horizon recursive optimal control. *Journal of Economic Dynamics and Control* 32(9) 2745-2787

[2] Campbell, F.T., Schlarbaum, S.E. 1994. Fading Forests: North American Trees and the Threat of Exotic Pests. New York: Natural Resources Defense Council.

[3] Clark, C. W. 1990 Mathematical Bioeconomics: The Optimal Management of Renewable Resources John Wiley and Sons.

[4] Cox, G.W. 1993 Conservation Ecology W.C. Brown Publishers, Dubuque, Iowa

[5] Keller, R. P., Lodge, D. M., Lewis, M. A. and Shogren, J. F. 2009 Bioeconomics of Invasive Species Integrating Ecology, Economics, Policy and Management Oxford University Press

[6] Pimentel, D. Lach, L., Zuniga, R. and Morrison, D. 2000 Environmental and Economic Costs of Nonindigenous Species in the United States, *BioScience*, 50, 53-65

[7] Sanchirico, J. N. and Wilen, J. E. 1999 Bioeconomics of Spatial Exploitation in a Patchy Environment. *Journal of Environmental Economics and Management* 37: 129-150

[8] Sanchirico, J. N. and Wilen, J. E. 2005 Managing Renewable Resource Use with Market-based Instruments: Matching Policy Scope to Ecosystem Scale. *Journal of Environmental Economics and Management* 50: 23-46

[9] Saphores, J. D. M. and Shogren, J. F. 2005 Managing Exotic Pests under Uncertainty: Optimal Control Action and Bioeconomic Investigations. *Ecological Economics* 52: 327-339

[10] Shogren, J. F. 2000 Risk Reduction Strategies against the "Explosive Invader" in Perrings, C., Williamson, M. and Dalmazzone, S. eds. The Economics of

Biological Invasions Edward Elgar, Cheltenham, UK

[11] Smith, M., Sanchirico, J. N. and Wilen, J. E. 2009 The Economics of Spatial-dynamic Processes: Application to Renewable Resources. *Journal of Environmental Economics and Management* 57: 104-121

[12] Wilen, J. E. Economics of Spatial-Dynamic Processes 2007 *American Journal of Agricultural Economics* 89 (5):1134-1144

CHAPTER 2

HISTORY AND BIOLOGY

2.1 History of gypsy moth invasion

For a lot of invasive species, it is impossible to determine how and when they are introduced into a new country. But the introduction of gypsy moth is obviously an exception. The gypsy moth was intentionally introduced into the United States in 1868 or 1869 by an amateur French entomologist named Etienne Leopold Trouvelot. He brought live gypsy moth eggs from Europe to Medford, Massachusetts because he hoped to cross the gypsy moth with a silk-producing species to develop a strain resistant to protozoan disease. He hoped to create a hardy silk-producer that was easy to raise and inexpensive to feed and hence create a lucrative silk market in the United States. In 1868 or 1869, several of Trouvelot's gypsy moths escaped from his home. Trouvelot knew the potential damage at that point and reported the incident to local authorities but received no response. Ten years later, the gypsy moth was established and the first outbreak happened around his neighborhood. (Liebhold et al 1989)

In 1889, the gypsy moth population exploded. The gypsy moth outbreak attracted the attention of local residents and they tried several ways to control the outbreak. The Massachusetts Legislature appropriated $50,000 to combat the pest. With the help of several prominent entomologists, a plan to completely eradicate all gypsy moths in the United States was devised and implemented over the next 10 years. The main methods they used include removing egg masses and spraying highly toxic arsenic-based insecticides on foliage.

By 1900, gypsy moths seemed to have varnished in Massachusetts because of the control methods. Despite the protest by The State's Gypsy Moth Commission and Board of Agriculture, the Massachusetts State Legislature stopped funding for the program. High population densities returned once again in 1905 and eradication efforts resumed. The gypsy moth was established in the New England States by 1920 spreading North, South and West of Massachusetts. At that point, control of gypsy moth became the goal because eradication of the pest was impossible. The control methods at this stage included an attempt at biological control by importing natural enemies from Europe and efforts to replace susceptible trees with less vulnerable species.

In the early 1940s, DDT (Dichloro-diphenyl-trichloroethane) was used to kill the gypsy moth. It was demonstrated to be an effective way of controlling the gypsy moth because it can kill populations of the moth quickly and completely. The federal government decided to use DDT on 3 million acres in Michigan, Pennsylvania, and New York as a test to see if eradication of gypsy moth was possible. The areas were sprayed in 1957 but the spraying program was stopped because of fierce opposition by the general public, environmentalists and scientists who were concerned about the pesticide's devastating overall effect on the environment. The use of DDT was initially limited and finally banned in the United States in the 1970s. (Sadof and Ellis 2009)

In 1992, a pilot project called “Slow the Spread” was started by the U.S. Department of Agriculture's (USDA) Forest Service and Animal and Plant Health Inspection Service (APHIS), along with the Department of Interior's National Park Service and eight State and university partners. The program is designed to slow the rate of natural spread through integrated pest management strategies. In 1999, the National Gypsy Moth Slow the Spread program was implemented along the entire 1200 mile gypsy moth frontier. Each year, it is estimated that the rate of natural spread of the gypsy moth has been reduced by 40 percent due to Slow the Spread program. The Slow the Spread method include: Trapping (intensive monitoring for new areas of infestation using pheromone-baited traps), suppression (mating disruption with pheromone flakes, mass trapping and spraying with Bt, diflubenzuron or Gypcheck) and regulatory work (Ensuring people comply with regulations when they move possibly infested articles). (APHIS 2003)

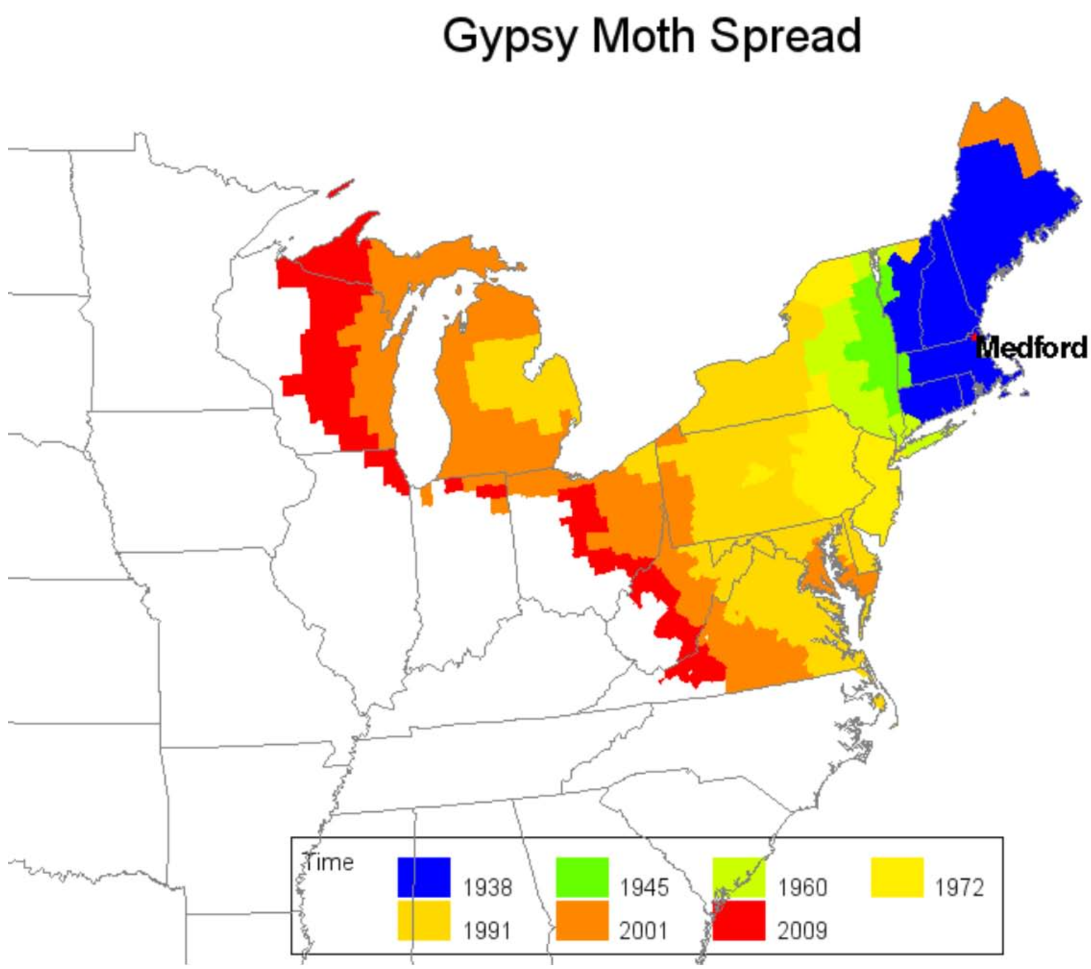


Figure 2.1 The Spread of Gypsy Moth

The gypsy moths is now established in 18 states (Connecticut, Illinois, Indiana, Maine, Maryland, Massachusetts, Michigan, New Jersey, New Hampshire, New York, North Carolina, Ohio, Pennsylvania, Rhode Island, Vermont, Virginia, West Virginia, and Wisconsin) and the District of Columbia as well as in eastern Canada.

2.2 Biology of gypsy moth

2.2.1 Life Cycle

Gypsy moth has one generation per year. Its life cycle is composed of four developmental life stages: egg, larva, pupa and adult.

The female moth lays egg masses in July and August in clusters of 100 to 1,000. While most eggs are laid on the bark of trees, females will also lay clusters in any sheltered location, including homes, vehicles, firewood, playground equipment, and stone walls. Egg masses are beige and about the size of a quarter. The egg stage lasts as long as eight to nine months and constitutes the overwintering stage of the insect.

Larvae (caterpillars) hatch from an egg mass the following April or May and begin devouring leaves. The caterpillar stage lasts for 10 to 12 weeks. Caterpillars are 1 to 2 inches long when fully grown, with hair-like structures along the entire length of their body. The caterpillar is grayish, with five pairs of blue spots followed by six pairs of red spots along their back, with yellow markings on the head. Larvae undergo a series of molts which allows the larvae to grow in size. Usually males undergo four molts and females undergo five. Young caterpillars feed during the day whereas older caterpillars feed at night.

Transformation from caterpillar to moth takes place during a 10– to 14–day period typically in July and August. At the end of the larval period, each larva has a pupation site, surrounds itself with a sparse silk net and then becomes a pupa. Pupae are reddish–brown and remain in the silk net for two weeks. After development is complete, the newly-formed adult breaks out of the pupal skin and starts its adult stage. Male pupae are about ¾ inch long; females, about 1 inch long. Adults emerge from pupae in July and August. Males appear one or two days before females and fly in zig-zag or straight patterns. Males usually fly less than a half mile from their site of emergence while females are incapable of flight.

Gypsy moths are light tan to dark brown and have blackish wavy bands across their forewings with arrowhead markings near the leading edge. Female moths are nearly white with faint, dark wavy bands on the forewings. With a wingspread of up to 2 inches, female moths are much larger than males. The antennae have a feathered appearance in the males but are long and thin in the females. Adult moths do not feed and live for only a few days.

2.2.2 Host

The gypsy moth caterpillar feeds on foliage. There are several kinds of trees which are preferred by gypsy moth caterpillars. They include: Oak, Birch (white and gray), Aspen, Apple, Basswood, Hawthorn, Willow, Witch hazel, Tamarack, Alder. The following tree species are not preferred by the gypsy moth, but can still be defoliated: Maples, Hemlock, Elms, Spruces, Boxelder, Chestnut, Hickories, Yellow Birch, Cherries, Black Birch, Cottonwood, Ironwood, Black Walnut, Beech, Butternut, Juniper, Pines. The following tree species are avoided by the gypsy moth: Ash, Locusts, Balsam Fir, Dogwoods, Scotch pine, Mountain Maple, Red and White Cedar (Liebhold et. al. 1995). The gypsy moth caterpillar can feed on as many as 300 species of plants.

Defoliation damage caused by gypsy moth also depends on time. The heaviest defoliation occurs from late June to early July. Trees will produce a second flush of foliage in mid-summer if two-thirds or more of the original foliage is lost. If the tree is defoliated before peak photosynthesis occurs, it must rely on remaining food reserves to produce the second flush of foliage. The additional stress placed on the tree when producing the second flush of foliage can lead to mortality of buds, twigs, and/or branches (Witter et. al. 1992).

The timing of defoliation is very important. A mid-season defoliation can be much more damaging to the tree than spring defoliation because the second flush of foliage does not have time to replenish the food reserves and the new buds do not have time to harden before the colder temperatures arrive (Gottschalk, 1993).

2.2.3Population Dynamics

Gypsy moth populations exist in four distinct phases. The innocuous phase (or endemic phase) is characterized by very low population levels. Gypsy moth life stages are often difficult to observe during this phase, which may persist for several years. The release phase usually takes place over one to two years and can result in population density increases of several orders of magnitude. The outbreak phase is characterized by populations high enough to cause noticeable tree defoliation. Outbreaks are rarely sustained for more than one to two years, after which high levels of mortality, primarily from starvation and disease, bring about a rapid population crash. This is the decline phase. These population changes often occur synchronously over wide geographical regions. However, there is little evidence that gypsy moth population outbreaks occur in regularly spaced cycles in North America (Elkinton and Liebhold 1990).

The population dynamics of the gypsy moth exhibits cyclical behavior. The timing of outbreaks is irregular and hard to predict, although there is some statistical evidence of a 10- to 11-year cycle (Liebhold et al. 2000).

Figure 2 shows the outbreak pattern in Northeastern U.S.

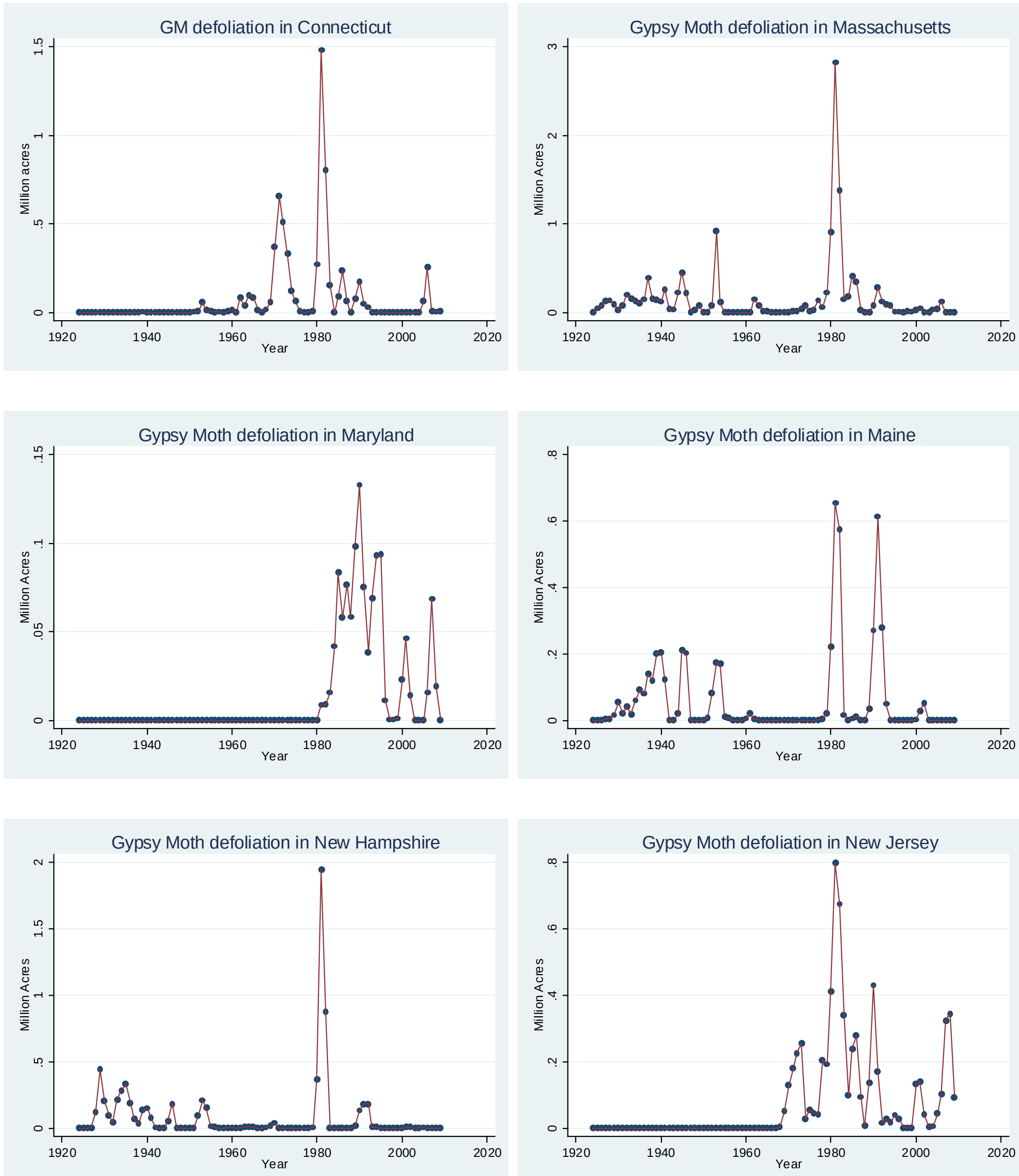
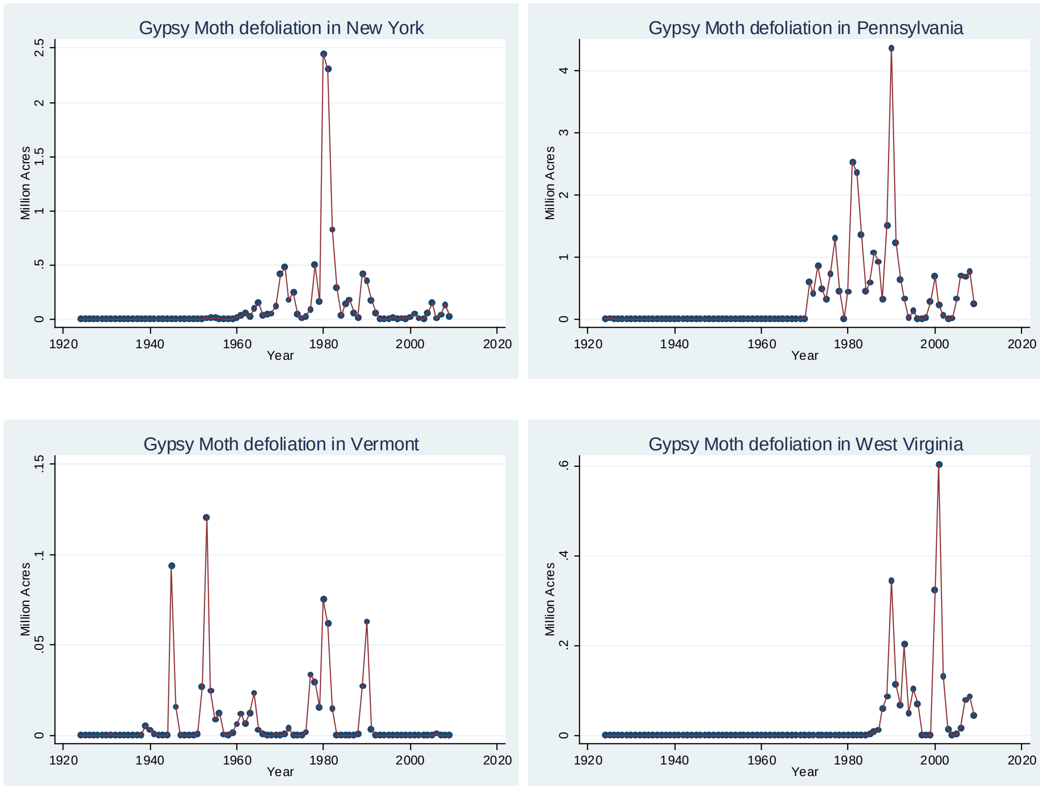


Figure 2.2 Defoliation in Northeastern U.S. (1924-2009)

Figure 2.2 Defoliation in Northeastern U.S. (1924-2009) (Continued)



2.2.4 Natural Enemies

Gypsy moth natural enemies can be divided into two categories: pathogen and predator. Pathogens include bacteria, the Nucleopolyhedrosis virus, Entomophaga fungus and parasitoids. Predators include: Invertebrate predators (e.g. ground beetles, ants and spiders), birds (e.g. Nuthatches, chickadees, towhees, vireos, orioles, catbirds, robins, and blue jays) and mammals (e.g. shrews and white-footed mice).

There is evidence that natural enemies contribute to the regulation of populations, although there is a controversy in their effectiveness. Efforts to control gypsy moth by rearing and releasing large numbers of parasitoids have not been successful. (Blumenthal et al. 1979)

Small mammals such as white-footed mice and shrews are considered to be the most important mortality agents that maintain gypsy moth population at low levels, but predation rarely plays more than a minor role in controlling numbers during an outbreak (Elkinton and Liebhold 1990). The nuclearpolyhedrosis virus (NPV) is usually the principal agent causing the decline of outbreak gypsy moth populations. Entomophaga Maimaiga was discovered to be causing considerable mortality in New England gypsy moth populations in 1989. It spreads very rapidly from New England and is now present for much of the area infested by the gypsy moth. (Hajek et al. 1990)

2.2.5 Dispersal

Gypsy moths are dispersed in two ways. Local dispersal occurs when newly hatched larvae hanging from host trees on silken threads are carried by the wind for a distance of up to one mile, although most go less than fifty meters. Eggs can be carried for longer distances. Long-distance jump dispersal occurs when people transport gypsy moth eggs thousands of miles from infested areas on human vehicles, firewood, household goods, and other personal possessions. Since females are flightless, these are the only two means for diffusion of the gypsy moth population.

This combination of long and short-distance dispersal mechanisms is known as stratified dispersal (Hengeveld 1989). Stratified dispersal can be divided into three stages: establishment of new colonies which are far from the moving population front, growth of individual colonies, and colony coalescence, which contributes to the advance of population front.

Another important feature that affects the colonization and establishment of gypsy moth is the Allee effect. The Allee effect implies the per capita birth rate declines at low densities because of the increased difficulty of finding a mate. Allee effect is not unique to gypsy moth. Other species also exhibit Allee effect, for example, many species of fish.

The Allee effect plays an important role in the dynamics of invasive species. Allee effects in an invader can cause longer lag times, slower spread and decreased probability of establishment (Taylor et al. 2005).

REFERENCES

[1] APHIS 2003 Plant Protection and Quarantine Factsheet

[2] Blumenthal, M. E., Fusco, R. A. and Reardon, R.C. 1979 Augmentative release of two established parasite species to suppress populations of the gypsy moth. *Journal of Economic Entomology* 72:281-288.

[3] Elkinton, J.S. and Liebhold, A.M. 1990. Population dynamics of gypsy moth in North America *Annual Review of Entomology* 35: 571-596.

[4] Gottschalk, K.W. 1993 Silvicultural guidelines for forest stands threatened by the gypsy moth USDA Forest Service NE Forest Experiment Station General Technical Report NE-171.

[5] Hajek, A.E, Humber, R.A., Elkinton, J.S., May, B., Walsh, S.R.A. and Silver, J. C. 1990. Allozyme and resriction fragment length polymorphism analyses confirm Entomophaga maimaiga responsible for 1989 epizootics in North American gypsy moth populations *Proceedings of the National Academy of Sciences* USA 87: 6979-6982.

[6] Hengeveld, R. 1989 *Dynamics of Biological Invasions* Chapman & Hall London

[7] Liebhold, A. M., Mastro, V. and Schaefer, P. W. 1989 Learning from the legacy of Leopold Trouvelot *Bulletin of the Entomology Society of American* 35: 20-21.

[8] Liebhold, A. M., Gottschalk, K.W., Muzika, R., Montgomery, M.E., Young, R., O'Day, K. and Kelley, B. 1995 Suitability of North American Tree Species to the Gypsy Moth: A Summary of Field and Laboratory Tests USDA Forest Service General Technical Report NE-211

[9] Liebhold, A. M., Elkinton, J., Williams, D. and Muzika, R. 2000 What causes outbreaks of the gypsy moth in North America? *Population Ecology* 42: 257-266

[10] Sadof, C. and Ellis, J. 2009 Gypsy Moth in Indiana Purdue Extension

[11] Taylor, C. M. and Hastings, A. 2005 Allee Effects in Biological Invasions *Ecology*

Letters 8:895-908

[12] Witter, J.A., Stoyenoff, J.L. and Sapio, F. 1992 Impacts of the gypsy moth in Michigan. Michigan Academician XXV 67-90

CHAPTER 3

WILLINGNESS TO PAY

3.1 Introduction

The gypsy moth, Lymantria dispar (L.), was accidentally introduced into Medford, Massachusetts in l869. Now it has spread to almost all of the northeastern states in the U.S. The gypsy moth has become a major defoliating pest of hardwood US forests and ornamental trees, especially oaks and aspen (Campbell and Schlarbaum 1994).

As an invasive species, the gypsy moth not only poses threats to the ecosystem, but also causes great economic damage. The damage from gypsy moth caterpillars can be categorized into two types. First defoliation of trees may result in subsequent tree mortality, causing a huge loss of commercial timber and tree removal expenses for urban and suburban property owners. Defoliation often occurs in populated areas. During a major outbreak gypsy moth caterpillars can diminish the enjoyment of outdoor recreation and their hair may trigger allergic reactions in some people. (McManus et al. 1979)

A key question in gypsy moth management is to evaluate its damage and investigate how the damage is associated with defoliation levels. Since the damage is composed of both market value (e.g. timber values) and nonmarket value (e.g. diminished amenity values), we employ a nonmarket valuation method to evaluate total damage. In this chapter, I elicit landowner’s willingness to pay for the gypsy moth control using a survey-based method to measure nonmarket values.

In order to elicit willingness to pay, the use of a discrete choice format within a contingent valuation survey is strongly recommended by the NOAA panel (Arrow et al. 1993) One advantage of the discrete choice format is that it mimics the decision making task that individuals face in everyday life since the respondent may accept or refuse the proposed bid.

While NOAA recommends the referendum format for eliciting WTP for non-market goods, Hanemann et al (1991) proposed the double bounded format to improve efficiency in contingent valuation estimation. A follow-up question in the double-bounded format constrains the part of the distribution for the respondent's WTP and increases the number of responses so that the function is fitted with more observations. (Haab and McConnell 2002)

In this chapter I investigate the relationship between economic damage and the level of defoliation. In previous studies in the 1980's, surveys were used to estimate household willingness to pay to avoid all damage. These studies did not examine how willingness to pay varies with the level of defoliation. This is important to know if a damage function is to be used within a bioeconomic model.

This chapter is organized as follows. The next section presents a literature review of the WTP for damage reduction. Section 3 describes the empirical models used in analyzing damage as a function of the level of defoliation. Section 4 reports the estimation result of econometric analysis and Section 5 concludes.

3.2 Literature Review

Payne at al. (1973) used the hedonic pricing method to indirectly evaluate the economic losses to residential property values from tree mortality caused by gypsy moth. The indirect valuation method was based on a hedonic study of the contribution of trees to property values in Amherst, Massachusetts (Payne and Strom, 1975). The authors used estimates of tree mortality from gypsy moth infestations to estimate how much property values might be reduced if gypsy moth induced tree mortality decreased property values at the same rate that large, healthy trees increase property value. The limitation of this study is that it is designed for residential property with a lot of trees on it and it is hard to extend to other circumstances. It does not consider partial defoliation case and nonmarket damages caused by gypsy moth, for example amenity loss and health effect.

Moeller et al. (1977) evaluated the influence of gypsy moth on homeowners and on managers of recreation areas. The results of this study showed that nuisance and defoliation effects of gypsy moth infestation were the main concerns of all ownership classes. This paper also reported the cost, financial losses due to infestation and recreation losses due to infestation. This work distinguishes from previous studies in that non-market value was first taken into consideration.

Jakus and Smith (1991) used the contingent valuation method to estimate a private household's willingness to pay for gypsy moth control programs in a ten-county area of Maryland and Pennsylvania. The two gypsy moth control programs that were included in the study differed in spatial coverage---the private plan would support spraying insecticide on residential property only, whereas the public plan would also spray surrounding public areas including parks and greenways. The results showed that individuals distinguish private and public aspects of landscape amenities and would like to pay more for the public program.

Haefele et al. (1992) estimated the total value of protecting high-elevation spruce-fir forests in the Southern Appalachian Mountains. Discrete and payment card willingness to pay questions are compared to derive that most forest protection benefits are nonuse values and the amount is substantial.

Miller and Lindsay (1993) used contingent valuation method to examine socioeconomic, demographic, and attitudinal factors which are likely to influence individual initiative to use control measures against gypsy moth infestation in three towns in New Hampshire. They found that the influencing factors include: the individual knowing the difference between the gypsy moth caterpillar and the eastern tent caterpillar; the individual being a homeowner rather than a renter; the number of acres of land accompanying the individual's dwelling; the number of trees on the individual's property; the individual's gender; and the individual's level of income. But the main reasons for individual to use control measures are aesthetic damage and the nuisance caused by gypsy moth infestation. Miller and Lindsey (1993) also estimated WTP for state gypsy moth control programs using the contingent valuation method on households living in New Hampshire. The mean willingness to pay estimates ranged from a low estimate of $53 ($23 per hectare) to a high estimate of $83 ($57 per hectare) annually for each household. The WTP values estimated in this study include a lot of the nonmarket value factors, such as aesthetic degradation, recreational loss, nuisance and impact on wildlife and ecosystems. This study differed from the earlier studies in that it evaluates the value of private property.

Jetter and Paine (2004) used contingent valuation method to estimate people's willingness to pay for different pest management options including chemical pesticide, bacterial insecticide and introduction of a specific natural enemy. Release of natural enemies was preferred to other two options and the willingness to pay is estimated at $485. The bacterial spray is ranked second and $131 was reported as WTP. Chemical pesticide is the least favored option and people would like to pay $23.

3.3 Contingent Valuation Survey

3.3.1 Survey Instrument

Both online and mail surveys were conducted from November 2008 through May 2009 to gather information about willingness to pay for gypsy moth control, along with information about socio-economic and other characteristics of the respondents. The sampling frame is land owners living in Northeastern U.S. This sampling frame is used because we want a portion of respondents to have some familiarity with the gypsy moth damage prior to receiving the questionnaire.

I sent out 900 e-mails with online survey URL link in it and we received 112 responses. In order to cover those land owners who don't have an e-mail address, we also sent out 200 mail surveys, receiving 52 responses. The response rates are 0.124 and 0.260 respectively for the online survey and mail survey.

According to the study of Kaplowitz et al. (2004), the response rate for mail survey is 0.315 with standard deviation 0.464, the e-mail survey response rate is 0.207 with standard deviation 0.405. The response rate of this study is below the average rate. The result may subject to nonresponse bias, we take this into consideration when we aggregate the total willingness to pay. We want to be on the conservative side, so we suppose that the willingness to pay for those who did not respond to our survey is different than that of respondents.

Before we ask the willingness to pay questions, we provide some background information about gypsy moth. Colored photographs are used to demonstrate different life stages of gypsy moth and how to distinguish gypsy moth with other commonly seen forest pests, such as the forest tent caterpillar and eastern tent caterpillar.

The survey questionnaire is composed of four parts:

The first part of the survey asks for basic information about the land owner's property. It covers the location of the property, the size of the property, types of trees present on the property, harvest history of the property and land management objectives.

The second part of the survey collects information about the land owners' past experience with gypsy moth outbreaks. Questions in this part include: whether they have experienced gypsy moth outbreak and the year and location of the gypsy moth outbreak, whether they regarded the outbreak as serious or not, whether they had taken any control measures to treat the gypsy moth and, if so how much they spent on these treatment.

The third part of the survey contained the willingness to pay questions. I provide pictures of different defoliation levels before the willingness to pay questions and then asked whether they would be willing to pay a dollar amount to reduce a certain level of defoliation. The initial question asked:

"Suppose you are a member of a local property owners association that is trying to control the Gypsy Moth in your area. Would you be willing to pay BID1, per acre, per year, to reduce defoliation from 20% (30%, 40%, and 50%) to 10% as indicated by the leaves shown above?"

BID1 is chosen from $10, $20, $50 and $100. The respondent's answer is a binary (Yes or No) variable. If the answer is yes, the respondent will be offered a higher bid. If the answer is no, then the respondent will be offered a lower bid.

We also provide follow-up questions:

Would you be willing to pay BID2, per acre, per year, to reduce defoliation from 20% (30%, 40%, and 50%) to 10% as indicated by the leaves shown above?

BID2 is equal to 2*BID1 if the answer is Yes to the initial question and 0.5*BID1 if the answer is No to the initial question. The answer to this question is also a binary variable (Yes or No).

The last section of the survey is the background information on respondent and respondent's household. Questions in this part includes: gender, highest education level, annual household income and family structure.

Table 3.1 Geographical distribution of the responses

State	Response	Percent
CT	3	1.96
IL	1	0.65
IN	4	2.60
MA	5	3.27
MD	3	1.96
ME	2	1.31
MI	4	2.61
NC	1	0.65
NH	2	1.31
NJ	20	13.07
NY	33	21.57
OH	3	1.96
PA	49	32.03
VT	15	9.8
WI	8	5.23
WV	1	0.65
Total	164	100

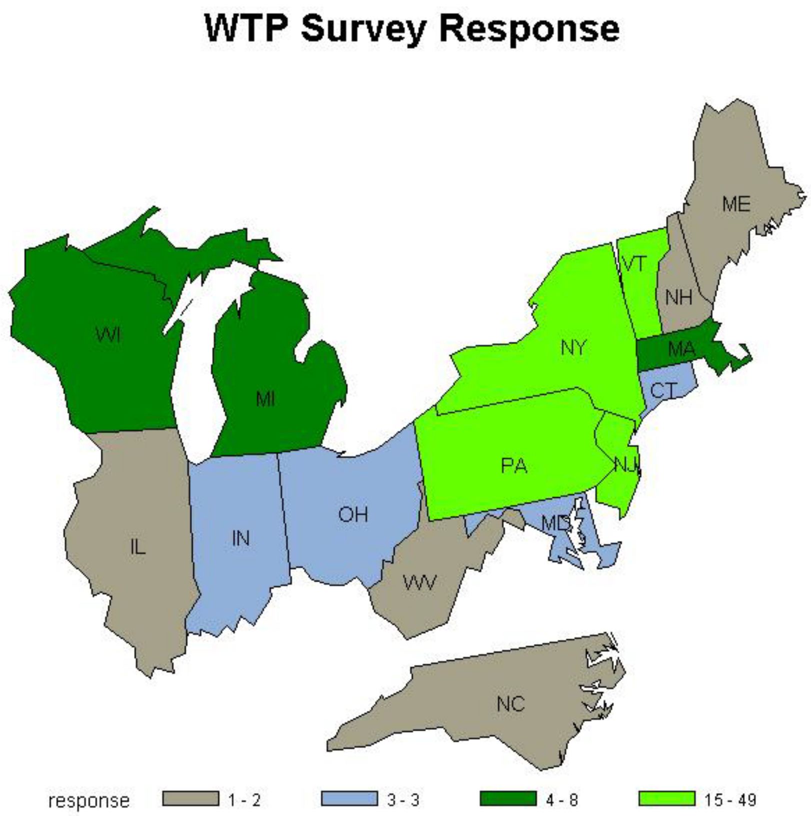


Figure 3.1 The Study Area

Of the 164 returned surveys, 10 of them miss important willingness to pay information. We delete those in our data set. There are 154 valid observations left.

The socioeconomic variables hypothesized to explain the level of WTP to reduce defoliation are summarized in Table 3.2. For example, 91.56 percent of the respondents have observed gypsy moth before, but only 18.83 percent of the respondents have taken actions to control it by their own.

Table 3.2 Definition of Variables

Variable	**Definition**	**Mean (Std. Dev.)**
LOCATION	Location of the property 1=Rural 2=Suburban 3=Urban	1.298701 (0.5616254)
AREA	Size of the property (acres)	91.0547 (216.0709)
OWN	Number of years you own the property	30.78667 (34.79848)
EXPENSE	Expense controlling most recent outbreak 1=Under \$500 2=\$500-\$999 3=\$1000-\$1999 4=\$2000-\$2999 5=\$3000-\$3999 6=\$4000-\$4999 7=Over \$5000	1.181818 (0.8514083)
HARVEST	1=Harvested before 0=Not	0.4573171 (0.4997006)
OBSERVATION	Observed gypsy moth before 1=Yes 0=No	0.9155844 (0.2789171)

Table 3.2 Definition of Variables (Continued)

SERIOUS	How serious is the defoliation 0=Don't know 1=Not serious 2=Somewhat serious 3=Very serious	1.733766 (1.428204)
MORTALITY	How important is potential tree mortality 1=Not important 2=Important 3=Most important	2.88961 (0.371566)
VISUAL	How important is visual effect 1=Not important 2=Important 3=Most important	1.857143 (0.6510783)
OUTDOOR	How important is diminished outdoor recreation 1=Not important 2=Important 3=Most important	1.733766 (0.6670803)
EXPERIENCE	Defoliation experience 1=Yes 0=No	0.5324675 (0.5005726)

Table 3.2 Definition of Variables (Continued)

ACTION	Actions taken by respondents 1=Yes 0=No	0.1883117 (0.3922364)
CAUSE	Defoliation cause tree mortality 1=Yes 0=No	0.3181818 (0.4672901)
EDUCATION	Education in years 0=None 1=High School 2= Two-Year College 3=Four-Year College/University 4= Post Graduate Degree	3.018293 (1.065191)
INCOME	Annual household income 1 ="Under $20,000" 2="$20,000-$29,999" 3="$30,000-$39,999" 4="$40,000-$49,999" 5="$50,000-$59,999" 6="$60,000-$69,999" 7="$70,000-$79,999" 8="$80,000-$89,999" 9="$90,000-$99,999" 10="$100,000-$149,999" 11="$150,000-$249,999" 12="$250,000-$499,999" 13="$500,000 and over"	6.036585 (3.676972)
OUTBREAK	Observed more than one outbreak 1=Yes 0=No	0.3246753 (0.4697812)

WTP is the dependent variable in the regression model, which is a binary variable of the associated bid value.

I also list the summary statistics for bid and response in the following table.

Table 3.3 Summary Statistics for Bid and Response

Var.	Definition	Mean (Std. Dev.)			
		10% Defoliation Reduction	20% Defoliation Reduction	30% Defoliation Reduction	40% Defoliation Reduction
BID1	Dollar value in the WTP survey	47.92683 (11.90327)	47.92683 (11.90327)	47.92683 (11.90327)	47.92683 (11.90327)
WTP1	Response to BID1 1=Yes 0=No	0.05594 (0.23062)	0.17123 (0.37801)	0.42857 (0.49656)	0.55405 (0.49876)
BID2	Follow-up bid	37.13415 (31.13921)	42.62195 (34.38973)	58.17073 (40.03459)	66.58537 (41.30448)
WTP2	Response to BID2 1=Yes 0=No	0.16429 (0.37187)	0.20000 (0.40144)	0.33333 (0.47305)	0.39865 (0.49128)

From this table above we can see that the bid price for 10%, 20%, 30% and 40% are the same at the initial time. Only 5.6% people would like to pay the bid price for 10% defoliation reduction, 17.1% respondents would like to pay for the 20% defoliation, 42.9% people would like to pay for 30% defoliation and more than half (55.4%) would like to pay for 40% defoliation reduction.

In the second round, the follow up bid price is changing. For 10% defoliation reduction, the bid price changed to 37.1 and for 20% defoliation reduction, the bid price decreased to 42.6. The bid price increased to 58.2 for 30% defoliation reduction and 66.6 for 40% defoliation reduction. For the follow up bid price, the willingness to pay is also increasing in defoliation reduction. 16.4% would like to accept the new bid price for 10% defoliation reduction and 20% for 20% defoliation reduction. 33.3% would like to pay the bid price for 30% defoliation reduction and 66.6% would like to pay for 40% defoliation reduction.

3.3.2 Estimation Framework

The model relating WTP to the independent variables listed above takes the form

$$WTP_i = bX_i + e_i \tag{3.1}$$

where WTP_i is the willingness to pay by the ith person, X_i is a vector of independent variables and e_i is an error term. Since we use a double-bounded dichotomous choice method, WTP is a latent variable (only bounds on the actual WTP amounts are observed). We adopt the estimation method proposed by Cameron et al. (1994). In that model, the bid amount and the response define a range for WTP. Independent variables and the coefficient vector, b, define the conditional mean WTP. In the double-bounded dichotomous choice model, the answer can be put into four categories: “yes/yes”, “yes/no”, “no/yes” and “no/no”. The probabilities of these four outcomes are denoted by P_i^{YY}, P_i^{YN}, P_i^{NY}, and P_i^{NN}, respectively. The probabilities can also be expressed in the following manner:

P_i^{YY} =Prob($B_i^0 \leq WTP and B_i^U \leq WTP$)=Prob($B_i^U \leq WTP$)

P_i^{YN} = Prob($B_i^0 \leq WTP and B_i^U > WTP$)

P_i^{NY} = Prob($B_i^0 > WTP and B_i^L \leq WTP$)

$$P_i^{NN} = \text{Prob}(B_i^0 > WTP and B_i^L > WTP) = \text{Prob}(B_i^L > WTP)$$

where B_i^0 is the first, randomly drawn bid offer, B_i^U is the upper bound bid, and B_i^L is the lower bound bid, all for individual i.

Assuming normally distributed errors, with the normal cumulative distribution function defined as $\Phi(\bullet)$, the distribution of the log-likelihood function for the ith individual is (Alberini 1995, Cameron et al. 1994):

$$\begin{aligned} LogL_i = d_i^{YY} \log(\Phi(z_{2i})) + d_i^{YN} \log(\Phi(z_{2i}) - \Phi(z_{1i})) + d_i^{NY} \log(\Phi(z_{1i}) - \Phi(z_{3i})) \\ + d_i^{NN} \log(1 - \Phi(z_{3i})) \qquad (3.2) \end{aligned}$$

where d_i^{YY}, d_i^{YN}, d_i^{NY} and d_i^{NN} are indicator variables for individual i, d_i^{ab} equals one when the outcome is ab (ab =YY, YN, NY, NN) and 0 otherwise, and where $z_{1i} = (B_i^0 - bX_i)/\sigma$, $z_{2i} = (B_i^U - bX_i)/\sigma$ and $z_{3i} = (B_i^L - bX_i)/\sigma$.

A probit model is used to estimate the coefficients of each independent variable. WTP to reduce a certain level of defoliation is expected to depend on the independent variables.

3.4 Results

Table 3.4, Table 3.5, Table 3.6 and Table 3.7 summarize the results for probit model for 10%, 20%, 30% and 40% defoliation reduction separately.

Table 3.4 Determination of WTP for 10% Defoliation

Variable	Coefficient	Std. Err.	z-value
BID10	-0.0019	0.00681	-0.28
LOCATION	-0.07193	0.213213	-0.34
AREA	-0.00067	0.000897	-0.74
OWN	-0.0019	0.004227	-0.45
EXPENSE	0.298242**	0.152011	1.96
HARVEST	0.064929	0.25624	0.25
OBSERVATION	0.242172	0.390943	0.62
SERIOUS	-0.18167*	0.105744	-1.72
MORTALITY	0.202001	0.308239	0.66
VISUAL	-0.02677	0.193549	-0.14
OUTDOOR	0.19227	0.172297	1.12
EXPERIENCE	-0.19175	0.272565	-0.7
ACTION	0.445903	0.30866	1.44
CAUSE	0.425533	0.307165	1.39
EDUCATION	-0.03573	0.154528	-0.23
INCOME	-0.04499	0.033459	-1.34
OUTBREAK	-0.38033	0.25547	-1.49
CONSTANT	-1.555	1.29347	-1.2

Obs.=292 Cluster=146 and log likelihood is -94.747668 chi-square statistics: 31.27 (significant at 0.05 df=17) Pseudo R2 statistics: 0.0981

* Significant at 0.1 level **Significant at 0.05 level *** Significant at 0.01 level

Table 3.5 Determination of WTP for 20% Defoliation

Variable	Coefficient	Std. Err.	z-value
BID20	-0.00954*	0.005	-1.91
LOCATION	-0.10152	0.194504	-0.52
AREA	-0.00096	0.000869	-1.1
OWN	-0.00076	0.004204	-0.18
EXPENSE	0.157363	0.155333	1.01
HARVEST	-0.08528	0.225583	-0.38
OBSERVATION	0.568154	0.407756	1.39
SERIOUS	-0.06758	0.090249	-0.75
MORTALITY	-0.08176	0.261775	-0.31
VISUAL	0.097696	0.183519	0.53
OUTDOOR	0.018349	0.165061	0.11
EXPERIENCE	-0.61598**	0.271665	-2.27
ACTION	0.896078***	0.317649	2.82
CAUSE	0.589801**	0.282235	2.09
EDUCATION	-0.00663	0.13422	-0.05
INCOME	-0.00346	0.028976	-0.12
OUTBREAK	-0.54483**	0.241153	-2.26
CONSTANT	-0.59806	1.087833	-0.55

Obs.=146 Cluster=146 and log likelihood is -123.70372 chi-square statistics: 39.56 (significant at 0.01 df=17) Pseudo R2 statistics: 0.1152

* Significant at 0.1 level **Significant at 0.05 level *** Significant at 0.01 level

Table 3.6 Determination of WTP for 30% Defoliation

Variable	Coefficient	Std. Err.	z-value
BID30	-0.00134	0.003074	-0.43
LOCATION	0.300013	0.183666	1.63
AREA	-0.00159**	0.000789	-2.01
OWN	0.001362	0.003553	0.38
EXPENSE	0.228051	0.143011	1.59
HARVEST	0.011599	0.1924	0.06
OBSERVATION	0.753642*	0.392069	1.92
SERIOUS	0.004007	0.077414	0.05
MORTALITY	0.096559	0.200928	0.48
VISUAL	-0.03359	0.147615	-0.23
OUTDOOR	0.270563*	0.148353	1.82
EXPERIENCE	0.127561	0.21809	0.58
ACTION	0.128152	0.292072	0.44
CAUSE	-0.06692	0.233667	-0.29
EDUCATION	-0.07046	0.113101	-0.62
INCOME	0.056881**	0.026079	2.18
OUTBREAK	-0.55163***	0.203465	-2.71
CONSTANT	-2.17642	0.85858	-2.53

Obs. =146 Cluster=146 and log likelihood is -170.96039 chi-square statistics: 33.17 (significant at 0.05 df=17) Pseudo R2 statistics: 0.0980

* Significant at 0.1 level **Significant at 0.05 level *** Significant at 0.01 level

Table 3.7 Determination of WTP for 40% Defoliation

Variable	Coefficient	Std. Err.	z-value
BID40	-0.00116	0.002918	-0.4
LOCATION	0.193072	0.186008	1.04
AREA	-0.00105*	0.000557	-1.89
OWN	0.001474	0.003329	0.44
EXPENSE	0.190521	0.117128	1.63
HARVEST	-0.24521	0.192357	-1.27
OBSERVATION	0.757124**	0.345112	2.19
SERIOUS	0.099054	0.075111	1.32
MORTALITY	-0.01756	0.240224	-0.07
VISUAL	-0.04838	0.147362	-0.33
OUTDOOR	0.22511	0.146427	1.54
EXPERIENCE	0.188396	0.219888	0.86
ACTION	0.1571	0.308474	0.51
CAUSE	-0.29957	0.24605	-1.22
EDUCATION	-0.01638	0.109384	-0.15
INCOME	0.079949***	0.02563	3.12
OUTBREAK	-0.46293**	0.222225	-2.08
CONSTANT	-1.69679	0.964206	-1.76

Obs. =146 Cluster=146 and log likelihood is -181.46143 chi-square statistics: 41.07 (significant at 0.01 df=17) Pseudo R2 statistics: 0.0991

* Significant at 0.1 level **Significant at 0.05 level *** Significant at 0.01 level

From the results above, the determinants of willingness to pay are the following.

For 10% defoliation reduction, significant determinants are expense and serious. The coefficient for expense is positive, which means respondents would be more likely to pay when they spend a lot in the last outbreak season. Seriousness has a negative impact on people's willingness to pay.

For 20% defoliation reduction, significant determinants include: bid price, experience, action, cause and outbreak. The negative coefficient of bid price means the respondents would be more willing to pay as the bid price goes down. Experience has a negative impact on the willingness to pay which means the respondents have never experienced defoliation on his property would like to pay more for the 20% defoliation reduction. Action has a positive effect on people's willingness to pay. If they have taken any actions before, they would like to pay more than those who have not. The coefficient of cause is positive. Respondents who have tree mortality on their properties because of the gypsy moth would like to pay more than others. Outbreak has a negative influence on willingness to pay. If the respondents have experienced more than one outbreak they tend to pay less for the gyps moth reduction program.

For 30% defoliation reduction, area, observation, outdoor, income and outbreak are significant factors affecting willingness to pay. Willingness to pay is decreasing in area. If the respondents' property is large, they would like to pay less per acre. The coefficient of observation is positive, which means people who have observed gypsy moth would like to pay more than people who haven't. The coefficient of outdoor is positive means respondents who put high values on outdoor activities would like to pay more for gypsy moth defoliation reduction. Income has a positive impact on willingness to pay which means respondents with higher household income would be more willing to pay than those with lower household income. Outbreak still has a negative impact on willingness to pay which is the same as the 20% defoliation reduction case.

For 40% defoliation reduction, area, observation, income and outbreak are significant determinants of willingness to pay. When the area is small, they would like to pay more for per unit gypsy moth control. Important factors also include observation. If they have observed gypsy moth before, they would like to pay more on gypsy moth control. Income level is also a significant determinant of willingness to pay. Willingness to pay is increasing in annual household income level. But if respondents have experienced an outbreak, their willingness to pay will decrease.

Table 3.8 Estimation of WTP

Reduced Defoliation Level	WTP ($ per acre)	95% Confidence Interval
10%	$2.969	(0.8264, 5.1159)
20%	$8.676	(4.9982, 12.3538)
30%	$42.001	(7.7807, 76.2213)
40%	$55.365	(44.8704, 65.8596)

The relationship between defoliation level and mean WTP is estimated as[1]:

$$y = \theta x^2$$

Where y is the damage and x is the defoliation level. Using solver in Excel, we solved for the optimal θ, which equals to 0.023265. This relationship will also be used in later chapters.

[1] A detailed calculation of coefficient θ is in Appendix Table A.2

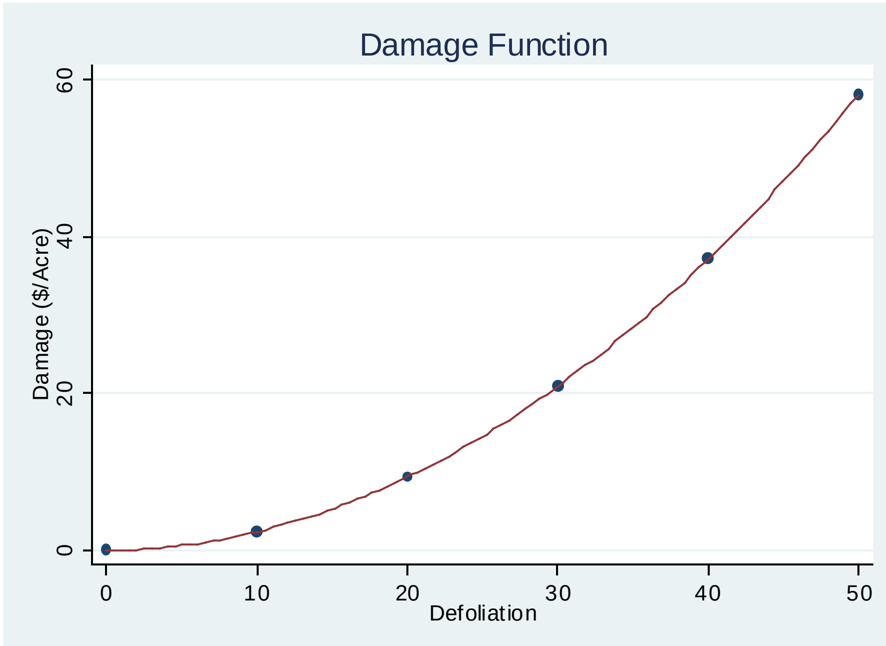


Figure 3.2 Damage Function

There are two approaches to calculate the total WTP. The first one is to multiply the unit WTP with the total population in the study area or total area. The second is to multiply the unit WTP with the total population or area and also multiply with the percentage who responds to the questionnaire. I adopt the second approach because people who respond to the questionnaire tends to care more about the gypsy moth problem and would like to pay more on the gypsy moth control program. The total willingness to pay is derived by the amount of per unit WTP times the total private forest land area[2] and times average response rate[3].

---

[2] Total private forest land is 120,842 thousand acres in the study area.

[3] Average response rate is calculated as the number of respondents divided by the total number of questionnaires sent out including online survey and mail survey. The average response rate used in the calculation is 15%.

Table 3.9 Estimation of Total WTP

Reduced Defoliation Level	Total WTP (Unit: Million)
10%	$53.81698
20%	$157.2638
30%	$761.3227
40%	$1003.563

3.5 Conclusions

In this chapter, I use contingent valuation method to elicit the willingness to pay for the gypsy moth control program. The willingness to pay can also be considered as the total damage the respondents want to avoid. This work is different from previous ones in that I analyze the willingness to pay for different defoliation levels and derive a damage function from the relationship. I also estimated the key determinants of respondents' willingness to pay.

Past experience is a key factor in determining willingness to pay. If a respondent has never observed gypsy moth before, they tend to pay less than other respondents who are familiar with the gypsy moth. The gypsy moth is a major devastating forest pest in Northeastern U. S. But for those who have never seen gypsy moth before, they can not distinguish it with other forest pests like tent caterpillar and other less harmful pests. They would like to pay less also because they are not fully aware of the damage gypsy moth may bring.

The probability of answering "Yes" to the willingness to pay question is significantly higher when the respondents have experienced more than one outbreak. This can be explained by several reasons. First, people who have experienced more than one outbreak have a larger probability of knowing how to control gypsy moth properly. Moreover, the tree structure may also change because of the gypsy moth defoliation effect. The trees left are less vulnerable to the gypsy moth. In addition, for areas where multiple outbreaks happen[4], government has taken actions to control it. Respondents can free ride the government control program and would like to pay less.

Socioeconomic factors will also have an impact on respondents' willingness to pay. Respondents with high income levels would like to pay more than others only when the reduced defoliation level is high enough (at 30% and 40% defoliation reduction level).

The relationship between defoliation and willingness to pay is not linear, but quadratic. Keep everything else equal, the damage of the gypsy moth may cause is increasing in defoliation levels in an increasing speed. This provides a benchmark for future bioeconomic analysis.

The limitation of this study is that more observations were from the infested area and relatively fewer observations were collected on the frontier of the gypsy moth invasion. We can better understand the geographical heterogeneity of willingness to pay distribution if we have more information on the willingness to pay of people living on the front.

---

[4] In this survey, 98% of respondents who have experienced more than one outbreak live in six states including: MA, MD, NJ, NY, PA and VT.

REFERENCES

[1] Alberini, A. 1995 Optimal Design for Discrete Choice Contingent Valuation Surveys: Single-bounded, Double-bounded and Bivariate Models *Journal of Environmental Economics and Management* 28: 187-306

[2] Arrow, K. Solow, R. Portney, P., Leamer, E. Radner, R., Schuman, H. 1993 Report of the NOAA Panel on Contingent Valuation Federal Register 58(10): 4602-4614

[3] Cameron, T. A. and Quiggin, J. 1994 Estimating Using Contingent Valuation Data from a Dichotomous Choice with Follow-Up Questionnaire *Journal of Environmental Economics and Management* 27: 218-234

[4] Campbell, F.T., Schlarbaum, S.E. 1994. Fading Forests: North American Trees and the Threat of Exotic Pests. New York: Natural Resources Defense Council.

[5] Haab, T.C. and McConnell, K.E. 2002Valuing Environmental and Natural Resource, Wallace E.Oates

[6] Haefele, M., Kramer, R. A., Holmes, T. 1992 Estimating the Total Value of Forest Quality in High-Elevation Spruce-Fir Forests In The economic value of wilderness, General Technical Report SE-78, Southern Forest Experiment Station, Research Triangle Park, NC.

[7] Hanemann, W. M. , Loomis J. , Kanninen B. 1991 Statistical efficiency of double-bounded dichotomous choice contingent valuation. *American Journal of Agricultural Economics* 73:1255–1263

[8] Jakus, P., Smith, K. V. 1991 Measuring Use and Nonuse Values for Landscape Amenities: a Contingent Behavior Analysis of Gypsy Moth Control Discussion Paper QE 92-07 Washington, DC Resources for the Future

[9] Jetter, K. and Paine, T. D. 2004 Consumer Preferences and Willingness to Pay for Biological Control in the Urban Landscape *Biological Control* 30: 312-322

[10] Kaplowitz, M. D., Hadlock, T. D. and Levine, R. 2004 A Comparison of Web and

Mail Survey Response Rates *Public Opinion Quarterly* 68: 94-101

[11] McManus, M. L., Houston, D. R. and Wallner, W. E. 1979 The Homeowner and the Gypsy Moth: Guidelines for Control Home and Garden Bulletin 227: 4-33. U.S. Department of Agriculture, Washington, DC

[12] Miller, J.D., Lindsay, B. E. 1993 Willingness to Pay for a state Gypsy Moth Control Program in New Hampshire: a Contingent Valuation Case Study *Journal of Economic Entomology* 86(3): 828-837

[13] Moeller, G. H., Marler, R. L., McCay, R. E., White, W. B. 1977 Economic Analysis of the Gypsy Moth Problem in the Northeast III Impacts on Homeowners and managers of Recreation Areas. Research Paper NE-360 Upper Darby, PA: Northeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture

[14] Payne, B. R., White, W. B., McCay, R. E. McNichols, R. R. 1973 Economic Analysis of the Gypsy Moth Problem in the Northeastern II Applied t Residential Property Research Paper NE-285 Upper Darby, PA: Northeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture

[15] Payne, B. R. and Strom, S. 1975 The Contribution of Trees to the Appraised Value of Unimproved Residential Land *Valuation* October/November: 36-45

CHAPTER 4

POPULATION DYNAMICS MODELS

4.1 Introduction and Literature Review

To investigate the outbreak pattern of the gypsy moth, biologists use mathematical models to capture the dynamics of the gypsy moth. In the first part of this chapter, I will review the literature from both biology and economics. By reviewing and integrating the biology and economics of the gypsy moth I hope to tell a more complete story.

Many insect populations, including forest defoliators, exhibit episodic outbreaks. Research into the biological and environmental causes for these episodic outbreaks has produced a sizeable literature in both theoretical biology and field studies of actual insect populations. Theoretical biologists have shown that it is possible to generate outbreak behavior in a variety of models, including host-parasitoid and host-pathogen models. These models are typically based on two or more nonlinear difference or differential equations and, depending on model structure and the value of specific parameters, are capable of generating large-amplitude, long-period cycles. [5]

For example, consider the density-dependent Nicholson-Bailey model

$$N_{t+1} = N_t e^{r(1-N_t/K)-aP_t}$$
$$P_{t+1} = N_t(1-e^{-aP_t})$$

where N_t is a host species and P_t is a parasite. The parameters are $r > 0$, the intrinsic growth rate of the host without the parasite, $K > 0$ equilibrium host density without the parasite, and $a > 0$, a parameter affecting the fraction of the host

[5]For a survey of host-parasitoid models see Varley *et al*. (1973). In human populations, viruses and bacteria are sometimes referred to as *microparasites,* while worms are referred to as *macroparasites*. The classic three-equation, Susceptible-Infected-Removed (SIR), model of infectious disease is an example of a host-pathogen system. Models of infectious disease are described in Hethcote (1976) and Anderson and May (1979).

population that escapes parasitism. This system has been studied by Beddington *et al*. (1975) and is capable of producing locally stable steady states, stable limit cycles, cycles of $5n$ periods, $n = 1,2,...$, and deterministic chaos. [Also see the discussion of this system in Edelstein-Kashet (1988, Chapter 3).]

The outbreak cycles of actual insect populations typically do not follow the precise regularity of cycles generated by host-parasitoid or host-pathogen models. The gypsy moth population oscillates strongly through its range. At peak population levels, egg masses may reach a density of 5,000 per acre. Dwyer *et al* (2004) show that the episodic outbreaks of forest defoliators might be explained by a model that includes both a generalist predator, a specific pathogen, and one or more random variables to account for environmental variability.[6] Predators of the gypsy moth include parasitic insects (wasps and flies), birds (chickadees, blue jays, nuthatches, robins, blackbirds, and starlings), and small mammals (mice, shrews, chipmunks, and squirrels). As noted earlier, there are two potential pathogens, a fungus (*Entomophaga maimaiga*) and a nuclear polyhedrosis virus which will kill susceptible caterpillars when they consume foliage that has been contaminated by infectious cadavers. During an outbreak, it may be a pathogen (fungus or virus) which will cause the gypsy moth population to crash back to endemic levels. They use a three-equation, nonlinear model to describe the change in the insect population, the change in pathogen density, and a third equation that implicitly determines the current-period rate of infection in the insect population.

---

[6] A generalist predator will rely on multiple food sources and its density may respond weakly or not at all to changes in the insect population. A generalist predator will typically modify the equation of insect dynamics via a *predator response function*, such as the functions described by Holling (1959). This may have the advantage of not requiring a separate difference or differential equation for the predator. A specific pathogen will significantly infect a portion of the insect population (often fatally) and typically requires its own difference or differential equation.

Bjørnstad *et al*. (2008) modify Dwyer *et al*. (2004) by introducing a fourth, nonlinear equation describing the dynamics of the general predator. Both Dwyer *et al*. (2004) and Bjørnstad *et al*. (2008) are excellent examples of modeling efforts to produce dynamic behavior that is more consistent with field observations. This added realism comes at a cost. The analysis of bifurcation regions in parameter space becomes more difficult (computationally intensive) and when the insect population of interest produces significant economic damage, the problem of optimal pest management may be intractable. Bioeconomics meets biocomplexity.

The contribution of this chapter is to show how the bioeconomics of pest management might be accomplished in the face of biocomplexity. I became interested in these issues when an entomologist was trying to determine the value of a fungal pathogen in controlling the spread of the gypsy moth. This fungus (*Entomophaga maimaiga*) has the potential to partially control the dynamics of existing populations and to slow the spread of the gypsy moth to Midwestern and Southeastern States. *Entomophaga maimaiga* has not been used to commercially control the gypsy moth, however *Bacillus thuringiensis* or Bt, a naturally occurring soil bacteria, has been sprayed in infested areas and is a moderately effective microbial insecticide. I will introduce defoliation damage and control costs and then numerically solve for the optimal gypsy moth threshold to apply a Bt spray. The optimal gypsy moth threshold that triggers the Bt is the threshold that minimizes the discounted sum of damage and control costs.

The remainder of this chapter is organized as follows. Next section presents what I regard as the two most plausible biological models of gypsy moth dynamics. I then modify the four-equation model to allow for biological control by a Bt spray. Section 3 summarizes the base-case calibration of these models, presents numerical results, and explores the sensitivity of the optimal threshold to key bioeconomic parameters. The last section provides conclusions for the chapter and suggests lines for future research.

4.2 Bioeconomic Model

The first model, developed by Dwyer *et al*. (2004), uses the following notation. N_t is the gypsy moth population and Z_t is the pathogen density at the start of year t. Gypsy moth caterpillars go through a series of molts. The interval between a molt is called an instar. While there may be five or six instars, there is only one generation per year. The fraction of the gypsy moth population that becomes infected by the pathogen during year t is denoted by I_t and is *implicitly determined* by Equation (4.1).

$$1 - I_t = \{1 + (\frac{\overline{\upsilon}}{\mu k})(N_t I_t + \rho Z_t)\}^{-k} \tag{4.1}$$

where μ is the rate of decay in infectiousness, ρ is the relative susceptibility of early-stage instars to infection, $\overline{\upsilon}$ is an average transmission rate, and k is the inverse of the squared coefficient of variation in transmission rates. The parameters $\overline{\upsilon}$ and k presume that transmission rates follow a gamma distribution [Dwyer *et al*. (2004, p.342)]. At the start of each year, including $t = 0$, N_t and Z_t will be known and Equation (1) must be numerically solved for $0 < I_t < 1$ that equates the Left-Hand-Side (LHS) to the Right-Hand-Side (RHS).

After computing I_t, some fraction of the starting gypsy moth population will survive the pathogen, pupate, and mate. This fraction is given by $N_t(1 - I_t)$. The surviving fraction has an intrinsic growth rate given by $\lambda > 0$. Growth, however, is stochastic and the realized intrinsic growth rate is assumed to be given by $\lambda e^{\varepsilon_t}$, where e is the base of the system of natural logs and $\varepsilon_t \sim N(0,\sigma^2)$. The realized growth of the survivors becomes $\lambda e^{\varepsilon_t} N_t(1-I_t)$. As if contending with the pathogen were not enough, a general predator now reduces the realized growth of survivors according to a Type III predator-response function given by $(1-\frac{2abN_t}{b^2+N_t^{\,2}})$, where $0<a<1$ is the maximum fraction killed by the general predator and $b>0$ is the gypsy moth density supporting a. The combined effect of infection, stochastic growth, and predation leads to the following equation for the starting insect population in $t+1$.

$$N_{t+1} = \lambda e^{\varepsilon_t} N_t(1-I_t)(1-\frac{2abN_t}{b^2+N_t^{\,2}}) \tag{4.2}$$

Fortunately, the dynamics of the pathogen are more straightforward. Based on the number of infected caterpillars, $N_t I_t$, there will be a constant pathogen survival or carry-over rate, $f>0$, and the starting pathogen density in $t+1$ is given by

$$Z_{t+1} = f\lambda N_t I_t \tag{4.3}$$

Dwyer *et al*. (2004) do extensive computational analysis on a non-dimensionalized version of Equations (4.1) – (4.3), where the host (insect) and pathogen densities are rescaled to reduce the number of parameters. They analyze both the deterministic $(\sigma = 0)$ and stochastic $(\sigma > 0)$ systems, showing the different types of attractors in the $[\log_{10} N - \log_{10} P]$ phase plane. Their Figure 3 classifies the types of attractors existing in the system and shows both short-term and long-term dynamics. In the non-stochastic system, they observe sources, sinks, saddle-points, limit cycles, and a quasi-periodic attractor. With $\sigma = 0.05$, the insect and pathogen densities may never settle on a single attractor and the stochastic shocks may keep the system moving between different basins of attraction.

Bjørnstad *et al*. (2008) modify Equation (4.2), by swapping out the Type III predator response in Dwyer *et al*. (2004) for a Type II response which takes the form $\exp(-\frac{ab(2+\sqrt{3})P_t}{2(\lambda e^{\varepsilon_t} N_t(1-I_t) + b(2+\sqrt{3}))})$, where P_t is the density of the predator. The Type II predator response function is capable of producing weak or strong Allee effects.[7] Allee effects are thought to be important in gypsy moth dynamics [Johnson *et al*. (2006), Tobin *et al*. (2007)]. The parameters a and b determine the maximum predation rate and the level of N_t where a predator reaches "half saturation" [Bjørnstad *et al*. (2008, p.11)].

Bjørnstad *et al*. (2008) also introduce a dynamic equation for the generalist predator. The dynamics of the generalist predator are given by the iterative map $P_{t+1} = P_t e^{r(1-P_t/K)}$ where $r > 0$ is the predator's intrinsic growth rate and $K > 0$ is the predators carrying capacity. Because the predator has an extensive menu of prey species, the carrying capacity of the predator does not depend on N_t.

---

[7] A strong Allee effect will result in a net growth function, F(N), that exhibits a critical population size below which net growth is negative. A weak Allee effect results in a depensatory net growth function where net growth per capita, r(N)=F(N)/N increases for some initial interval for N.

This results in a four-equation model, where the infection rate and pathogen dynamics are unchanged from Dwyer *et al*. (2004).

$$1 - I_t = \{1 + (\frac{\bar{\upsilon}}{\mu k})(N_t I_t + \rho Z_t)\}^{-k} \qquad (4.1')$$

$$N_{t+1} = \lambda e^{\varepsilon_t} N_t (1 - I_t) \exp(-\frac{ab(2+\sqrt{3})P_t}{2(\lambda e^{\varepsilon_t} N_t (1 - I_t) + b(2+\sqrt{3}))}) \qquad (4.2')$$

$$Z_{t+1} = f \lambda N_t I_t \qquad (4.3')$$

$$P_{t+1} = P_t e^{r(1-P_t/K)} \qquad (4.4')$$

Equations (4.1′) – (4.4′) are capable of producing complex, irregular, outbreak dynamics that are consistent with field observations and hypothesized gypsy moth–pathogen–predator interactions in North America. The base-case parameter values adopted by Dwyer *et al*. (2004) and Bjørnstad *et al*. (2008) are as follows: $\bar{\upsilon} = 0.9$, $\mu = 0.32$, $k = 1.06$, $\rho = 0.8$, $\lambda = 74.6$, $a = 0.98$, $b = 0.05$, $f = 21.33$, $r = 2$, and $K = 4$. We simulate the system forward in time from initial conditions $N_0 = 1$, $Z_0 = 10$, and $P_0 = 3$. Figure 4.1 shows the phase-plane diagram when $\sigma^2 = 0$, corresponding to the deterministic system with no stochasticity in Equation (4.2′).

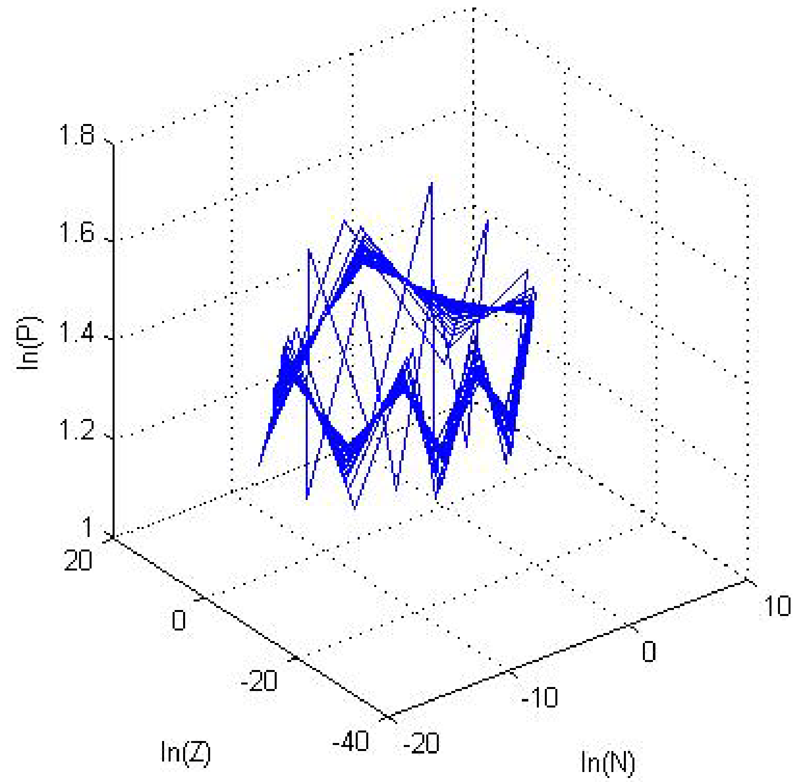


Figure 4.1 The Phase-Plane for Equations (4.1´) – (4.4´) with $\sigma^2 = 0$

In Figure 4.1, both the gypsy moth, N_t, and the pathogen, Z_t, are fluctuating in a cycle of approximately 10 years with the rate of infection remaining near 100% for two years following the collapse of the gypsy moth population. With $r = 2$, the predator, P_t, follows a two-year cycle.

Figure 4.2 shows the phase plane when $\varepsilon_t \sim N(0,0.09)$. The gypsy moth population and pathogen density again fluctuate in 10-year cycles while the predator follows a two-year cycle. The variance rate ($\sigma^2 = 0.09$), while not large enough to change the qualitative behavior of the system does produce a greater variance

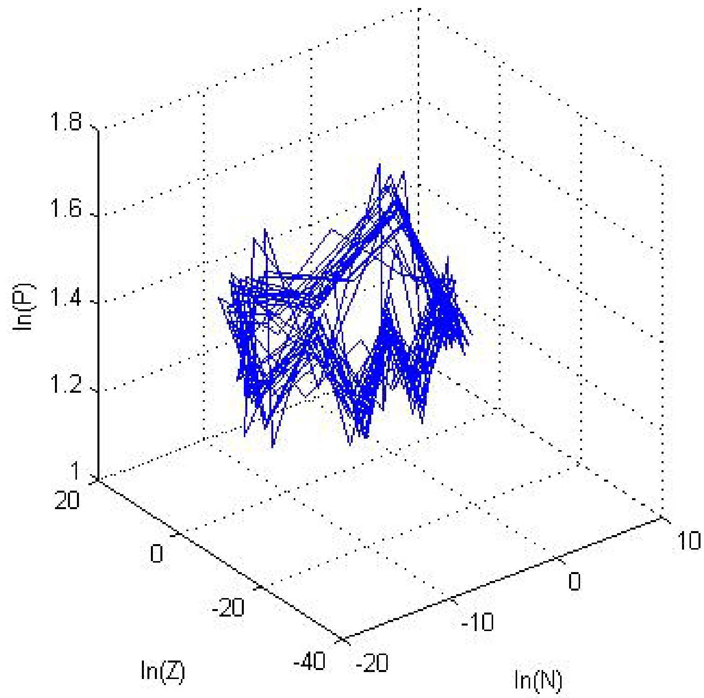


Figure 4.2 The Phase-Plane for Equations (4.1´) – (4.4´) with $\sigma^2 = 0.09$

(amplitude) in both N_t and Z_t. In both Figures 4.1 and 4.2, N_t peaks before Z_t. As N_t begins an outbreak, the rate of infection increases, followed by an increase in pathogen density that reinforces and gives momentum to the rate of infection. N_t crashes first, followed one period later by Z_t, and two periods (years) later by I_t.[8] This four-equation, nonlinear model accords well with the observed cycle of the gypsy moth in the mesic (maple-beech-birch) forests in the Northeastern United States.

We now introduce some economics into this biologically complex system.

[8] See Figure A.1 for a closer look in the first fifty years.

We consider a possible biological control. It involves the application of a Bt spray, which will induce additional mortality within the gypsy moth equation, but does not directly affect the pathogen or the infection rate. Aerial spraying of Bt is the most commonly used biological control for the gypsy moth. The application of a Bt spray modifies Equation (4.2´) to become

$$N_{t+1} = \lambda e^{\varepsilon_t} N_t (1 - I_t)(1 - mS_t) \exp\left(-\frac{ab(2+\sqrt{3})P_t}{2(\lambda e^{\varepsilon_t} N_t (1 - I_t) + b(2+\sqrt{3}))}\right) \qquad (4.2'')$$

where $0 < m < 1$ is the per acre mortality rate induced by a standard-dose Bt spray when $S_t = 1$ In years when no Bt is sprayed, $S_t = 0$.

The optimal threshold in this case will involve the minimization of the sum of discounted damage plus control cost. Because the application of Bt spray is standard treatment, we have information on the cost of using this biological control. We solve for the optimal threshold to spray the fungus assuming that the costs of producing the fungus and applying it are similar to the production and application of Bt by aerial spray.

Damage is based on the percentage of tree defoliation per acre, per year. To calculate damage we first need to rescale the gypsy moth population so that it is measured in egg masses per acre. This can be done by defining

$$X_t = \omega N_t \qquad (4.5)$$

Setting $\omega = 100$ rescales the fluctuations in N_t so as to produce fluctuations in X_t that range between a few and 4,500 egg masses per acre, consistent with field estimates.

The relationship between tree defoliation (as a percentage, per acre, per year) and egg mass density per acre at the start of a year has been studied by Gottschalk (1993) who specifies a logistic relationship given by

$$Y_t = 100/(1+ve^{-\gamma X_t}) \tag{4.6}$$

The best fit to Gottschalk's data points is given when $v = 7.248$ and $\gamma = 0.00173$.

From November, 2008, through May, 2009, we conducted an online survey to determine the willingness-to-pay by private property owners in the Northeastern United States to reduce gypsy moth defoliation. The results of that survey support a quadratic damage function of the form

$$D_t = \theta Y_t^{\,2} \tag{4.7}$$

where $\theta = 0.02$.

For both the Bt and fungal spray, we seek the optimal threshold policy

$$S_t = \begin{cases} 1 & if \quad X_t > X^* \\ 0 & if \quad X_t \le X^* \end{cases} \tag{4.8}$$

where the value of X^* is determined so as to minimize the discounted sum of damage and control costs. Because damage, D_t, is measured in dollars per acre in year t, we specify a cost per acre[9] for aerial spray of $c > 0$. We do not allow spraying in $t = 0$, so the objective function for either problem (the optimal

---

[9] See appendix Table A.1 for summary statistics of suppression cost.

Bt or the optimal fungal threshold) seeks to

$$\underset{X^*}{\text{Minimize}} \quad D = \sum_{t=1}^{200} \beta^t (D_t + cS_t) \tag{4.9}$$

where $\beta = 1/(1+\delta)$ is a discount factor and $\delta > 0$ is the discount rate. We choose time horizon $T = 200$ as our time horizon because we would like to simulate the history of gypsy moth population dynamics in 140 years (from 1869 to 2009) and we also want to predict the future population dynamics of the gypsy moth in the next 60 years. Another reason for choosing 200 as time horizon is that the discount coefficient after 200 years will be smaller than 5.78283×10^{-5}, which is negligible in the present value analysis.

For the Bt problem the objective functional is Equation (4.9) with constraints given by Equations (4.1´), (4.2´´), (4.3´), (4.4´), (4.5), (4.6), (4.7), and (4.8). The initial conditions for this problem were the same as those underlying the biological simulations shown in Figures 4.1 and 4.2; that is, $N_0 = 1$, $Z_0 = 10$, and $P_0 = 3$.

4.3 Results

The base-case bioeconomic parameters and initial conditions are summarized in Table 4.1.

Table 4.1 Parameters used in the bioeconomic model

Parameter	Meaning	Value
	Biological Parameters	
$\overline{\upsilon}$	Average transmission rate	0.9
μ	Rate of decay in infectiousness	0.32
k	Inverse of the squared coef. of variation in transmission rate	1.06
ρ	Relative susceptibility of early stage instars to infection	0.8
λ	Intrinsic growth rate of surviving gypsy moth	74.6
a	Maximum fraction killed by the general predator	0.98
b	The gypsy moth density supporting a	0.05
f	Pathogen survival rate (carry-over rate)	21.33
r	Predator's intrinsic growth rate	2
K	Predator's carrying capacity	4
ω	Scale factor	100
v	Defoliation coefficient	7.248
γ	Defoliation coefficient	0.00173
σ	Standard deviation of log-normal variable ε	0.3
	Economic Parameters	
θ	Damage coefficient	0.02
δ	Discount rate	0.05
c	Unit spray cost ($/Acre)	20
m	Gypsy moth mortality rate due to spray	0.8
	Initial Conditions	
N_0	Initial value of gypsy moth population density	1
Z_0	Initial value of pathogen population density	10
P_0	Initial value of predator population density	3

We begin by solving for the optimal threshold (egg mass density per acre at the start of the year) that would justify spraying Bt when $\sigma^2 = 0$. This is done by specifying a range, $(X_U{}^* - X_L{}^*)$ and an increment, ΔX^*, and then determining the value of $D = \sum_{t=1}^{200} \beta^t (D_t + cS_t)$ for $X^* = X_L{}^* + j\Delta X^*$ where $j = 0,1,2..., J = (X_U{}^* - X_L{}^*)$. We start with a coarse-grid search where $X_L{}^* = 100$, $X_U{}^* = 4{,}000$ and $\Delta X^* = 100$ implying $J = 39$. The plot of D as a function of X^* is shown in Figure 4.3.

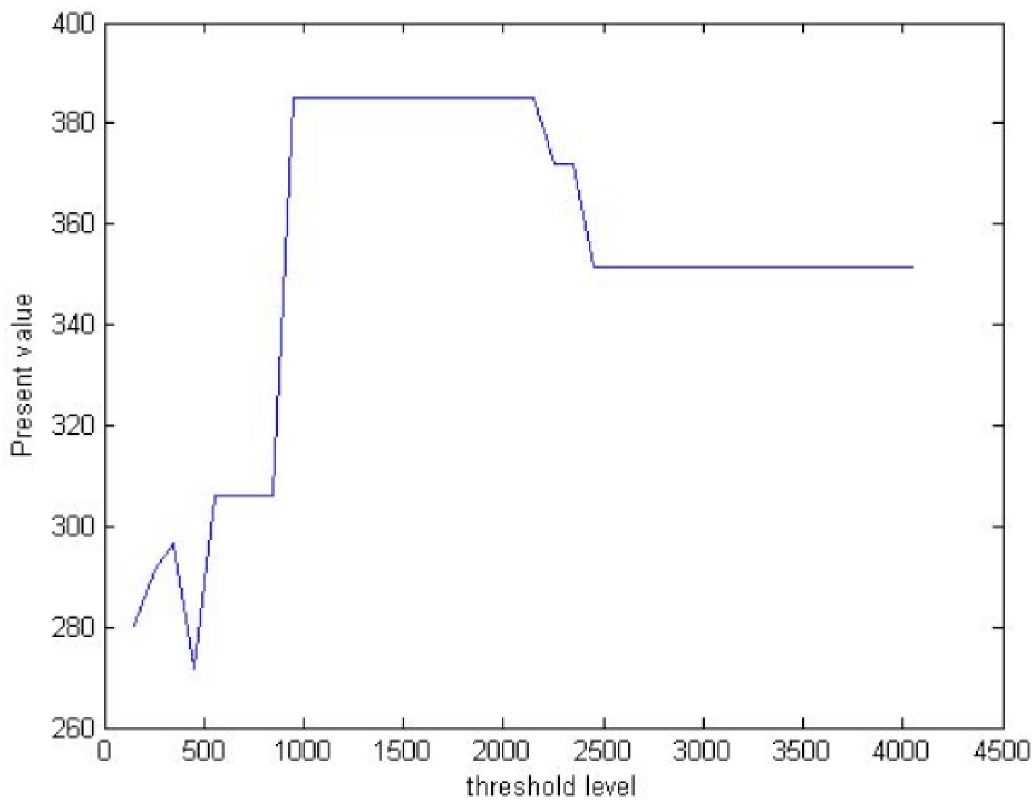


Figure 4.3 Coarse-Grid Search for X* when $\sigma^2 = 0$

The coarse-grid plot reveals that the minimization of the sum of discounted damage and spraying costs does not result in a smooth convex function for $D = D(X^*)$. Rather, D is discontinuous in X^* and graphically appears as a series of line segments with multiple, non-unique, local minima. This would be a treacherous optimization problem for a local solver. From this coarse-grid search, it appears that the global minimum may be in the vicinity of $X^* = 500$. We then refine our search using $X_L{}^* = 200$, $X_U{}^* = 1000$, $\Delta X^* = 10$, implying $J = 80$. The results of this finer-grid search are shown in Figure 5 where the optimal threshold is $X^* \approx 450$ associated with a minimized present value of $D^* \approx 270$ per acre.

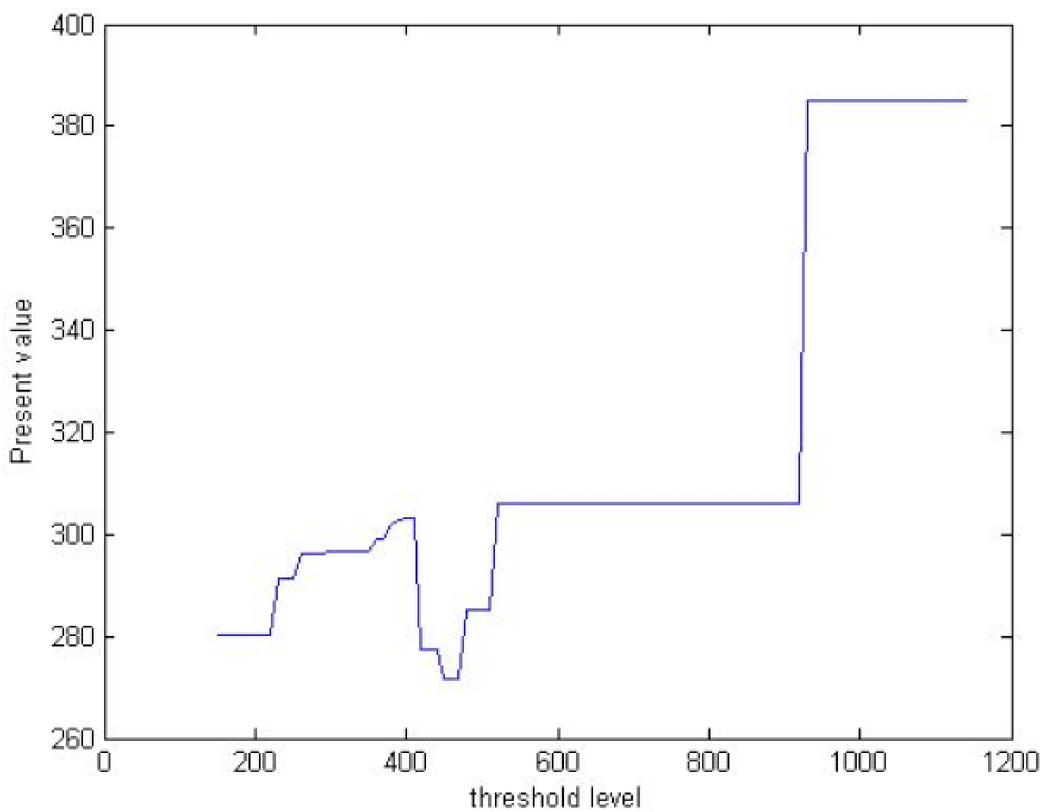


Figure 4.4 Fine-Grid Search for X* when $\sigma^2 = 0$

With stochastic biocomplexity, $\sigma > 0$ in Equations (4.2´´), for control using Bt. For $\sigma > 0$ and for a particular control, our analysis is based on finding the optimal threshold in each of 1,000 stochastic simulations, each with a 200-year horizon. We then plot the distribution of X^*s and D^*s and calculate descriptive statistics. Table 4.2 reports optimal thresholds (X^*) and present values (D^*) for $\sigma = \{0,0.1,0.2,0.3,0.4,0.5\}$ for Bt.

Table 4.2 Optimal Thresholds and Present Values for Different σ

σ	X^* Using Bt	D^* Using Bt	Damage if no control	Damage Reduction
0.0	450	268.6960	347.6926	22.72%
0.1	450	253.7839	315.8901	19.66%
0.2	400	238.6358	297.3309	17.45%
0.3	400	237.7689	274.5022	13.38%
0.4	350	232.6683	252.7672	7.95%
0.5	300	227.5748	234.4497	2.93%

For Bt, we see that the optimal threshold declines as the variance in the growth rate of the gypsy moth increases. For the Bt model, the average, present value of damage and control cost decreases as the variance increases and landowners shift to lower thresholds to apply Bt.

The damage when there is no control also decreases with σ, but the percentage of damage reduction declines. When there is no uncertainty in population dynamics, the threshold control policy can reduce the defoliation damage by 22.72%. But when the uncertainty in population dynamics become bigger, the threshold policy is less effective. The threshold policy will be ineffective when σ is equal to or bigger than 0.5. The reasoning behind this is that the population in the next period of time can not be well predicted by the population in the previous time period, Bt spray can not reduce the population density in the next period of time for sure.

When $\sigma = 0.3$, we did sensitivity analysis on X^* and D^* with respect to changes in the economic parameters: θ, the damage parameter, δ, the discount rate, c the cost of application (spraying cost per acre), m, the mortality rate induced by the Bt spray. The qualitative results are summarized in Table 4.3.

Table 4.3 Comparative Statics of X^* and D^* when $\sigma = 0.3$

Parameter	ΔX^* (Bt)	ΔD^* (Bt)
$\Delta\theta$	-	+
$\Delta\delta$	+	-
Δc	+	+
Δm	-	-

The comparative statics reported in Table 4.3 are based on a comparison of the values for X^* and D^* for $\sigma = 0.3$ (from Table 4.2) with small changes in one economic parameter. New values for X^* and D^* were then calculated, again based on 1,000 stochastic simulations, each of 200 years in length. In Table 4.3 we see that an increase in θ, lowers the optimal threshold to spray and increases the average present value of damage and control costs. An increase in δ increases the threshold to spray and reduces the average present value of damage and control costs for both Bt.

As expected, an increase in spraying cost will increase the threshold to spray and the average present value of damage and control costs. The mortality rate, m, only appears in the Bt control model, where an increase in m (the effectiveness of the Bt spray) will lower the optimal threshold and the average present value of damage and control costs.

4.4 Discussions and Conclusions

While this chapter is primarily concerned with the management of the gypsy moth, it raises some issues that we feel speak more broadly to bioeconomics and biocomplexity. We will summarize these issues first, then discuss what the analysis tells us about management of the gypsy moth, and conclude with a brief description of what we hope will be a sequel, estimating the value of strategies to slow the spread of the gypsy moth within a spatial-dynamic model.

The first generation of bioeconomic models gave us important insight into the optimal management of renewable resources and allowed economists to identify how taxes or a system of tradable quota might mimic *user cost* (the current-value shadow price of the resource) to promote better resource management. Most of these early models were biomass (or lumped-parameter) models, often using the logistic equation to describe net biological growth. Simple biomass models, however, were often incapable of producing the biological complexity found in the field. Theoretical biology has moved on to multi-equation, nonlinear systems in a search of models to better describe reality.

This move to biocomplexity has put the onus on resource economists to find ways to optimize biocomplex systems, when the underlying resources (or pests) are important to society. Our ability to optimize a nonlinear dynamical system containing two or more state variables is limited and in our study of the gypsy moth we have fallen back on coarse-grid-then-fine-grid search techniques and extensive stochastic simulation. There is no guarantee that biocomplex optimization problems will exhibit global convexity or concavity, and local solvers may be inappropriate. Analysis at the intersection of bioeconomics and biocomplexity will likely require intensive computation and thoughtful analysis to design code and to discover hidden structure. In the gypsy moth model, more efficient code for repeated solution of the implied infection rate greatly improved our ability run extensive, stochastic simulations in minutes, instead of hours.

While our model was calibrated for the gypsy moth, the structure may be appropriate, with modification, to other forest defoliators. By discovering hidden structure in a specific model, one might be discovering structure common to a broader class of models. Finding efficient ways to optimize models with a newly discovered structure may require an advancement in numerical methods and search algorithms. We feel that the analysis of problems at the intersection of bioeconomics and biocomplexity can lead to improved resource management *and* the advancement of operations research and computer science.

What have we learned about the gypsy moth, where it has become established in the northeastern U.S.? The first conclusion is that we are dealing with a complex biological system where predators and pathogens play complex roles in the periodic outbreaks of this species. Dwyer *et al*. (2004) and Bjørnstad *et al*. (2008) have identified plausible biological models which can be calibrated to produce outbreak behavior that mimics the gypsy moth in the mesic forests of the northeastern U.S. There may be other models that could produce similar results, but these models, with a general predator and specific pathogen, are compelling, based on what we know about the life cycle of the gypsy moth and the ecological system of which it is a part.

Further, these models allowed for the introduction of economic values and the formulation of a dynamic optimization problem. Specifically, we needed to introduce the mortality or increased infection from spraying Bt. After the biological model has been modified for control, we needed to determine the cost of control ($c > 0$) and the damage from defoliation ($\theta > 0$). We restricted our search to finding the best threshold policy. In this complex optimization problem, the optimal policy should depend on not only X_t, but on *all* state variables in the system; *i.e.*, Z_t, P_t, and I_t, as well. In biocomplex systems many state variables are *not observable*. The resource economist is trying to optimize a partially observable system, and may have to settle for finding the best threshold policy for variables that are observable (such as egg mass density per acre).

While we have reasonable estimates of aerial spraying costs per acre, we are still refining our estimates of $\theta > 0$, based on a contingent valuation survey. Estimates of the mortality rate from spraying Bt are consistent with those reported in the control literature. While out thresholds, X^*, and average present values for damage and control costs, D^*, seem reasonable we hope that the review of this manuscript by knowledgeable entomologists and resource economists will allow for a "reality check" and refinement. We offer the numerical values in Tables 4.2 and 4.3 as our current estimates of best thresholds and the likely present value for damage and control costs, per acre.

Finally, this chapter was concerned with the best threshold policies for management of *established* gypsy moth populations. Our next challenge is to identify the best biological model for gypsy moth *diffusion*, and then to model the effectiveness, cost, and value of strategies to slow the spread. There are now a large number of invasive species that are not feasible or optimal to eradicate, and where the optimal policy is one that might slow their spread across a landscape. As suggested by Jim Wilen (2007), optimal control in models of diffusion are likely to be an important area of future research, with invasive species providing the *raison d'etre*.

REFERENCES

[1] Anderson, R. M. and R. M. May. 1979 Population Biology of Infectious Diseases, part I *Nature*, 280:455-461.

[2] Beddington, J. R., Free, C. A., and J. H. Lawton. 1975. Dynamic Complexity in Predator-Prey Models Framed in Difference Equations *Nature*, 255:58-60

[3] Bjørnstad, O. N., Robinet, C., and A. M. Liebhold. 2008 Geographic Variation in the North American Gypsy Moth Population Cycles: Subharmonics, Generalist Predators, and Spatial Coupling Working Paper, Version 27-1, 39 pages

[4] Dwyer, G., Dushoff, J. and S. H. Yee. 2004. The Combined Effects of Pathogens and Predators on Insect Outbreaks *Nature*, 430:341-345

[5] Edelstein-Keshet, L. 1988. *Mathematical models in biology*. Random House/ Birkhaüser Mathematical Series, New York

[6] Gottschalk, K. W. 1993 Silvicultural Guidelines for Forest Stands Threatened by the Gypsy Moth USDA Forest Service NE Forest Experiment Station General Technical Report NE-171

[7] Heathcote, H. W. 1976. Qualitative Analysis of Communicable Disease Models *Mathematical Bioscience*, 28:335-356

[8] Holling, C. S. 1959 The Components of Predation as Revealed by a Study of Small Mammal Predation on the European Pine Sawfly," *Canadian Entomologist*, 91:293-320

[9] Johnson, D. M., Liebhold, A. M., Tobin, P. C., and O. N. Bjørnstad. 2006. Allee Effects and the Pulsed Invasion by the Gypsy Moth *Nature*, 444:361-363

[10] Liebhold, A. M. and J. S. Elkinton. 1989 Characterizing Spatial Patterns of Gypsy Moth Defoliation *Forest Science* 35:557-68

[11] Liebhold, A. M. Sharov, A. A. and P. C. Tobin. 2007 Population Biology of Gypsy Moth Spread Chapter 2 in *Slow the Spread: A National Program to*

Manage the Gypsy Moth, (P. C. Tobin and L. M. Blackburn, eds.) U.S.D.A. Forest Service, Northern Research Station, General Technical Report, NRS-6

[12] Miller, N. 2008. To Kill a Caterpillar *Grow* (Wisconsin's magazine for the life sciences) 1(2):6

[13] Tobin, P. C., Whitmire, D. M., Bjørnstad, O. N., and A. M. Liebhold. 2007. Invasion Speed is Affected by Geographic Variation in the Strength of Allee Effects *Ecology Letters*, 10:36-43

[14] Varley, G. C., Gladwell, G. R., and M. P. Hassell. 1973. *Insect Population Ecology: An Analytic Approach*, 135-153, Blackwell Scientific, Oxford.

[15] Wilen, J. E. 2007 Economics of Spatial-Dynamic Processes *American Journalof Agricultural Economics*, 89(5):1134-1144.

CHAPTER 5

DIFFUSION MODEL

5.1 Introduction and Diffusion Models Review

The study of invasive species requires dynamic models. Deterministic as well as stochastic dynamic models have been employed to address the management of invasive species (e.g. Taylor and Burt 1984, Wu 2001, Eiswerth and Kooten 2002, Saphores and Shogren 2004). There are still some research questions in resource economics that can not be answered without resorting to spatial-dynamic models. For example, how should one design a control policy in a diffusive environment? What is the optimal level of control? When and where should the optimal control be applied? In spite of the bulk of work in either dynamic economics or spatial economics, the economic literature of spatial-dynamic studies is still sparse. In this chapter we use spatial dynamic models to study the optimal management of invasive species in both space and time.

The dispersal of invasive species is often modeled using a reaction diffusion model. (e.g. Skellam 1951, Mollison 1977 and Marsula and Wissel 1994)

The reaction diffusion model simulates dispersal as a continuous random walk but can not address the heterogeneous spread problem. In response to this shortcoming, Sharov and Liebhold (1998) discuss how to use barrier zones to control the invasive species in a framework of stratified diffusion. The contribution of this paper is that they address the spatial heterogeneity problem using a new model of a population front. They also incorporate a lot of biological details which makes the paper biologically more realistic. Models of invasive species in much of the literature have based on individual growth and individual diffusion. Sharov and Liebhold (1998) model colony establishment and colony growth which provides a different perspective to the diffusion of an invasive species.

They decompose the spread of gypsy moth into two main pathways, a long-distance dispersal that leads to establishment of new colonies and local dispersal where colonies increase in area. They explicitly divide the area at the front of an invasive species into infested zones, transition zones and uninfested zones. The zones are connected by the spread of the invasive species. Then they set up the relationship between the colonization rate, the distance from the population front, and the relationship between population numbers in a colony and colony age. They use simulation techniques to predict the effect of slow the spread policies and conclude that the project will result in a 54% reduction of spread rate.

The limitation of this paper is that they only consider one possibility of control, but in reality there are a lot of control methods, for example eradication, prevention and suppression. These methods can be applied individually or combined to tackle the invasive species problem. It is necessary to investigate the interaction of these policies and their combined effect on the invasive species control problem.

Another possible extension is the incorporation of cost and benefit. If it is possible to quantify the magnitude of the benefit and cost of different control policies, one could evaluate whether the policy is worthwhile or not. There is a control cost associated with slowing the spread and there is a corresponding benefit associated with the reduced damage. If they can compare the different slow the spread regimes and evaluate the program based on cost benefit analysis, the result will be more interesting and more useful to guide future management practices.

Recently, Sanchirico et al. (2010) set up a two-patch spatial model to address the optimal control of invasive species. The contribution of this paper can be divided into two parts; the first one is that it integrates the biological system into an economic system to analyze the spatial control of an invasive species. The second part is that it takes into consideration many possible control methods, including inspections, removal efforts, sustainable land management practices, habitat restoration and less damaging production activities. It also studies the interaction of these control policies.

This paper uses a stylized bio-economic meta-population model to capture three types of invasion and dispersal mechanisms that link the transmission processes with the population biology of the species. Moreover, the model explicitly examines how the ecological mechanism causes economic damages. Because of the nonlinear nature of the model, it is solved using numerical analysis.

The finding of this paper is that control strategies in the presence of spatially linked processes interact in a nonlinear way over a heterogeneous landscape. The research shows that models that use proxies for spatial processes based on spatial heterogeneity can make erroneous predictions for which even the direction of error is difficult to determine.

The limitation of this paper is that it employs a two-region economic-ecological model. It can not address the control problem in a large scale. For example, if we need to put monitoring efforts along an invasive species front, how should we distribute the monitoring efforts when we have limited budget? The two-patch model is so simplified that it cannot provide enough insights for the actual invasive species management in a big landscape.

Another strand of literature I want to refer to is the work about the optimal management of renewable marine resources, the research problem is a little different from invasive species management, but they share something in common. The research method is similar in that in a meta-analysis model is used to predict the location and abundance of a fish stock.

Sanchirico and Wilen (2005) employ a metapopulation model where the subpopulations are connected by a dispersal processes and are affected by the spatial distribution of harvesting effort. The paper studies the optimal spatial allocation of harvesting effort and finds that the optimal instruments reflect the interplay between the spatial gradient of rents and the spatial gradient of biological dispersal. The contribution of this paper is that the bio-economic model incorporates a patchy description of the biology with a regulated open access depiction of the harvesting industry and the model can be extended to understand the question of how to design fiscal instruments to account for spatial and intertemporal externalities in other contexts.

Costello and Polasky (2008) study the optimal harvest of a renewable resource in a generalized stochastic spatially explicit model. They solved for an analytical solution. Stochasticity is an important feature in resource management.

This chapter develops a realistic invasive species diffusion model and incorporates an economic and management component into the model to address the invasive species management problem. It is necessary to model the heterogeneity of both biological process and economic costs because the interaction of these two determines the distribution of management efforts. More broadly speaking, such a model can also be used to understand the management of other migratory renewable resources, such as marine resources and biodiversity.

Using the gypsy moth as an example, I develop a spatial dynamic model and employ it to estimate the benefits from controlling the spread of an invasive species to areas beyond the current front. In the bioeconomic model, efforts to slow the spread will reduce diffusion rates. Slowing the spread will postpone and therefore reduce the present value of damages and control costs for areas not yet infested by the gypsy moth. The benefit of a gypsy moth control will be estimated as the present value of damage, without any actions to slow the spread, less the present value of damage and control costs when some set of actions (a control strategy) are undertaken. Control actions include the application of chemical and biological controls, the use of pheromones to disrupt mating and a quarantine of items from known infested areas. A finite number of control strategies, involving a combination of these actions, will be evaluated.

The contributions of this chapter can be summarized as follows. First, I combine spatial and temporal analysis to study the economic impact of invasive species, specifically the gypsy moth. It will provide new insights to invasive species management. I also extend the model into a stochastic setting and evaluate the effect of uncertainty on the optimal control strategy.

Second, biological analysis and economic analysis are integrated to inform policy. There is a large biological literature on invasive species. However, the economic literature is relatively sparse and largely separated from the biological literature. Although bioeconomic interaction is crucial in invasive species management, management agencies primarily rely on natural scientists for advice, party because highly simplified population models are often used in economic analysis. In invasive species control, an economic analysis is meaningful only when key biological aspects are taken into account. In this chapter, some key biological attributes are taken into consideration and I also evaluate how these features will affect the optimal control policy.

Finally, I develop new computational methods for invasive species management. Previously, there were two strands of study, one concentrating on analytical modeling and the other focusing on GIS analysis. I combined numerical analysis with graphical analysis to predict the spread of gypsy moth. The result of this study can also be used to evaluate the risk of gypsy moth infestation in the future.

The rest of this chapter is organized as follows. I review the mathematics and biological application of diffusion models. I then set up a bioeconomic model and simulate the spread of the gypsy moth population. The final section concludes this chapter.

5.2 Spatial Dynamic Model

In renewable resource economics, spatial dynamic processes attract increasing attention because of their wide application in epidemics, invasive species spread, animal disease transmission, subsurface contamination of porous aquifers, shoreline change, biological reserve site selection, provision of ecosystem services and management of marine and terrestrial species (Smith et al 2009). Some seminal works have been done in this line of research. Brock and Xepapadeas (2008, 2010) performed conceptual analysis to study the management of ecosystems. Sanchirico and Wilen (1999, 2005) used metapopulation models to study the management of spatially explicit renewable resources. Smith and Wilen (2003) studied sea urchin fishery in northern California which explicitly incorporated the behavior of fishermen in response to spatial marine reserve closure. Lenhart and Bhat (1992) studied the optimal control of wildlife damage by migratory small mammal populations using a nonlinear distributed parameter control model.

There are also some spatial dynamic models focused on invasive species. Skellam (1951) developed one of the first applications of a diffusion model dealing with the spread of the muskrat in central Europe. Fisher (1937) earlier described a similar model of the spread of advantageous genes through a population. Skellam's (1951) model combined Fick's law of diffusion with an exponential model of population growth.

Skellam (1951) developed a partial differential equation below and used it to analyze the spread of muskrats.

$$\frac{\partial N}{\partial t} = D(\frac{\partial^2 N}{\partial x^2} + \frac{\partial^2 N}{\partial y^2}) + rN$$

where $N = N_{xyt}$ is population density at time t and location (x, y) ,

$D(\frac{\partial^2 N}{\partial x^2} + \frac{\partial^2 N}{\partial y^2})$ is the diffusion process with diffusion coefficient D, rN is population growth with intrinsic growth rate r. In this model, it is assumed that all individuals disperse and reproduce simultaneously and there is no variation in dispersal capabilities.

This model predicts that the spatial distribution of the population is a two dimensional normal distribution.

$$N_{xyt} = \frac{N_{000}}{4\pi Dt} e^{(rt - \frac{x^2 + y^2}{4Dt})}$$

Where N_{000} is the initial population density at time $t = 0$ a location $(x, y) = (0,0)$, the center of a circle.

In this model, the rate of spread at the invasion front can be analytically solved as:

$$V = 2\sqrt{rD}$$

The prediction of this model matches the observed rate of spread for a lot of invasive species (Andow et al. 1990 and Shigesada and Kawasaki 1997). Habitat heterogeneity could affect spread via either habitat-dependent rates of movement, as measured by D, or habitat-dependent rates of population increase, as measured by r. Models have been developed for disease spread in a human populations that incorporate heterogeneity of the landscape over which the organism spreads (e.g. Cliff et al., 1981).

5.2.1 Biological Model

In this chapter, we use Johnson et al. (2006) model instead of Bjørnstad et al. (2008) model as a benchmark model to describe the diffusion process of the gypsy moth because it reflects key characteristics of diffusion process and also it is a simplified version of gypsy moth population dynamics which makes the analysis computationally feasible. The gypsy moth-predator–pathogen model would be too complex if we extend it into a diffusion model.

They use a theoretical model with parameter values estimated from long-term monitoring data to show how an interaction between Allee effects (declining population growth at low densities) and stratified diffusion (most individuals disperse locally, but a few seed new colonies by long-range movement) can explain the invasion process.

Suppose there are I locations, let n_{it} be the population density at location i (i=1,2,…1000) at the end of time t (which for the gypsy moth might be considered as generation t). The dynamics of population growth can be written as a stochastic, second-order Moran–Ricker model:

$$x_{it} = (an_{i,t-1})(e_i^{\,v})(n_{i,t-1}{}^{\alpha} n_{i,t-2}{}^{\beta})\left(\frac{n_{i,t-1}{}^{2}}{c^2 + n_{i,t-1}{}^{2}}\right) \tag{5.1}$$

Where x_{it} is the population density after growth in location i at the beginning of time t. The parameter a is the maximum population growth rate. The second term, $e_i^{\,v}$, is a unit-mean, log-normally distributed environmental shock to population growth. The parameters α and β represent the strength of first- and second-order density-dependence, respectively. The fourth term represents an Allee effect, for which c = 0 denotes no Allee effect. In the simulation, we consider a one-dimensional landscape consisting of 1,000 locations. Each location is 1 mile in length, the area of each plot is 1 square mile.

The population dispersal will also affect the population density in location i. The population dispersal may take two forms, short-distance dispersal (also called local dispersal) and long-distance dispersal (also called jump dispersal). The population density in location i in time t is equal to:

$$n_{it} = d_1 x_{it} + \sum_{\substack{j=i-m \\ j \neq i}}^{i+m} d_{ij}^{\tau} x_{i-j,t} + \phi x_{i-k,t} \tag{5.2}$$

The population in location i comes from three sources: the population that stays at location i, the local dispersal from its immediate neighborhood and gypsy moth carried via vehicle from far away. Each location cell is linked through dispersal with a maximum local dispersal distance of m miles (d_{ij} is the distance between cells i and j). Jump dispersal, according to a stratified diffusion process, has a very small proportion of the population (ϕ) that jumps a distance (k) as randomly selected from a uniform distribution on the integers $[k_1, k_2, \ldots k_N]$.

5.2.2 Economic Model

Now we introduce some economics into the system. We consider two possible biological controls. The first involves the application of a Bt spray, which will induce additional mortality within the equation. Aerial spraying of Bt is the most commonly used biological control for the gypsy moth. The application of a Bt spray modifies the population growth function and equation (1) becomes

$$x_{it} = (a n_{i,t-1})(e_i^{\,v})(n_{i,t-1}{}^{\alpha} n_{i,t-2}{}^{\beta})\left(\frac{n_{i,t-1}{}^2}{c^2 + n_{i,t-1}{}^2}\right)(1 - mS_{it}) \tag{5.3}$$

where $0 < m < 1$ is the per acre mortality rate induced by a standard-dose Bt spray when $S_{it} = 1$ In years and locations where no Bt is sprayed $S_{it} = 0$.

The second potential biological control involves the introduction of quarantine mechanism. The quarantine requires anyone moving trees or tree products or other outdoor articles such as patio furniture, trucks, campers or pallets out of quarantine areas have these articles inspected and assured free of gypsy moth in any life stages before shipping them to a non-quarantined area. The purpose of this quarantine is to prevent the artificial spread of gypsy moth. Suppose the quarantine effort level is E_{it} in location i and time t. Effort level is measured as the number of hours worked to discover the existence of gypsy moth. The cost of quarantine efforts is the wage rate. In order to be conservative on the cost, we use minimum wage rate as a proxy. Equation (5.1) stays the same, but the dispersal process was changed by efforts. Then equation (5.2) is changed into:

$$n_{it} = d_1 x_{it} + \sum_{\substack{j=i-m \\ j \neq i}}^{i+m} d_{ij}^{\tau} x_{i-j,t} + \phi x_{i-k',t} \qquad (5.4)$$

If the effort level is greater than zero, the k' follows a uniform distribution on the integers $[0, k_1, k_2, \ldots k_N]$. The mechanism of quarantine efforts can be understand in this way. Quarantine efforts alter the distribution of coefficient k so that the jump dispersal is influenced.

We will determine the optimal threshold to apply the Bt spray when the biological system is described by Equations (5.2), and the optimal quarantine effort E_{it} to prevent the spread of gypsy moth when the biological system is described by Equations (5.4).

The optimal threshold case will involve the minimization of the sum of discounted damage plus control cost. The relationship between tree defoliation (as a percentage, per acre, per year) and egg mass density per acre at the start of a year has been studied by Gottschalk (1993) who specifies a logistic relationship given by

$$Y_{it} = 100/(1 + \nu e^{-\gamma n_{it}}) \qquad (5.5)$$

From November, 2008, through May, 2009, we conducted a survey to determine the willingness-to-pay by private property owners in the Northeastern United States to reduce gypsy moth defoliation. The results of that survey support a quadratic damage function of the form

$$D_{it} = \theta Y_{it}^{2} \tag{5.6}$$

where $\theta = 0.02$.

The control variable in this model is S_{it} and it follows an algorithm below:

$$S_{it} = \begin{cases} 1 & if \quad spray \\ 0 & if \quad not \quad spray \end{cases} \tag{5.7}$$

where the value of S_{it} is determined so as to minimize the discounted sum of damage and control costs. Because damage, D_t, is measured in dollars per acre in year t, we specify a cost per acre for aerial spray of $c > 0$. We do not allow spraying in $t = 0$.

5.2.3 Optimization Problem

Spray Policy

The objective function for the spray problem is to minimize the expected discounted net present value of damage and cost over T time horizon and I locations by choosing different levels of spraying across space and over time:

$$\underset{S_{it}}{Min}\, E\{\sum_{i=1}^{I}\sum_{t=1}^{T}\beta^{t}(D_{it} + C_{it})\} \tag{5.8}$$

where $\beta = 1/(1+\delta)$ is the discount factor and $\delta > 0$ is the discount rate. For the Bt control problem the objective function is Equation (5.8) with constraints given by Equations (5.2), (5.3), (5.5), (5.6), (5.7).

Bellman's (1957) principle of optimality implies that the optimal spray policy must satisfy the following equation:

$$V_t(n_t) = \min_{S_t} \sum_{i=1}^{I} [D_t + C_t] + \beta E_t \{V_{t+1}(n_{t+1})\}$$

Which is subject to the conditions (5.2), (5.3), (5.5), (5.6), (5.7).

Quarantine Policy

The objective function is also to minimize the expected discounted net present value of damage and cost over T time horizon and I locations. The only difference is that the choice variable in this question is the level of quarantine efforts.

$$\underset{E_{it}}{Min}\, E\{\sum_{i=1}^{I} \sum_{t=1}^{T} \beta^t (D_{it} + C_{it})\} \tag{5.9}$$

where $\beta = 1/(1+\delta)$ is the discount factor and $\delta > 0$ is the discount rate. For the quarantine control problem the objective function is Equation (5.9) with constraints given by Equations (5.1), (5.4), (5.5), (5.6).

Bellman's (1957) principle of optimality implies that the optimal spray policy must satisfy the following equation:

$$V_t(n_t) = \min_{E_t} \sum_{i=1}^{I} [D_t + C_t] + \beta E_t \{V_{t+1}(n_{t+1})\}$$

Which is subject to the conditions (5.1), (5.4), (5.5), (5.6).

5.3 Results

Parameters used in the simulation are listed in Table 5.1 below.

Table 5.1 Parameters used in the model

Parameter	Meaning	Value
a	Maximum population growth rate	26.3
α	First-order density dependence	-0.1
β	Second-order density dependence	-0.4
v	Environmental Stochasticity	$N(0,0.4)$
c	Allee effect coefficient	39.4
d_1	Local dispersal population proportion	0.9
τ	Exponential kernel	-0.19
ϕ	Jump dispersal population proportion	0.005
m	Mortality due to spray	0.8
ν	Defoliation coefficient	7.248
γ	Defoliation coefficient	0.00173
δ	Discount rate	0.05
θ	Unit damage	0.02
c	Unit cost	20
I	Total locations	1000
T	Total time horizon	200

Data used in simulation comes from two sources.Defoliation data comes from USDA gypsy moth digest. The gypsy moth spread frontier data are from the historical county level gypsy moth quarantine status (US code of Federal Regulations) as reported by USDA since 1934 and compiled in a geographical information system.

We simulate the bioeconomic model and get the following result:

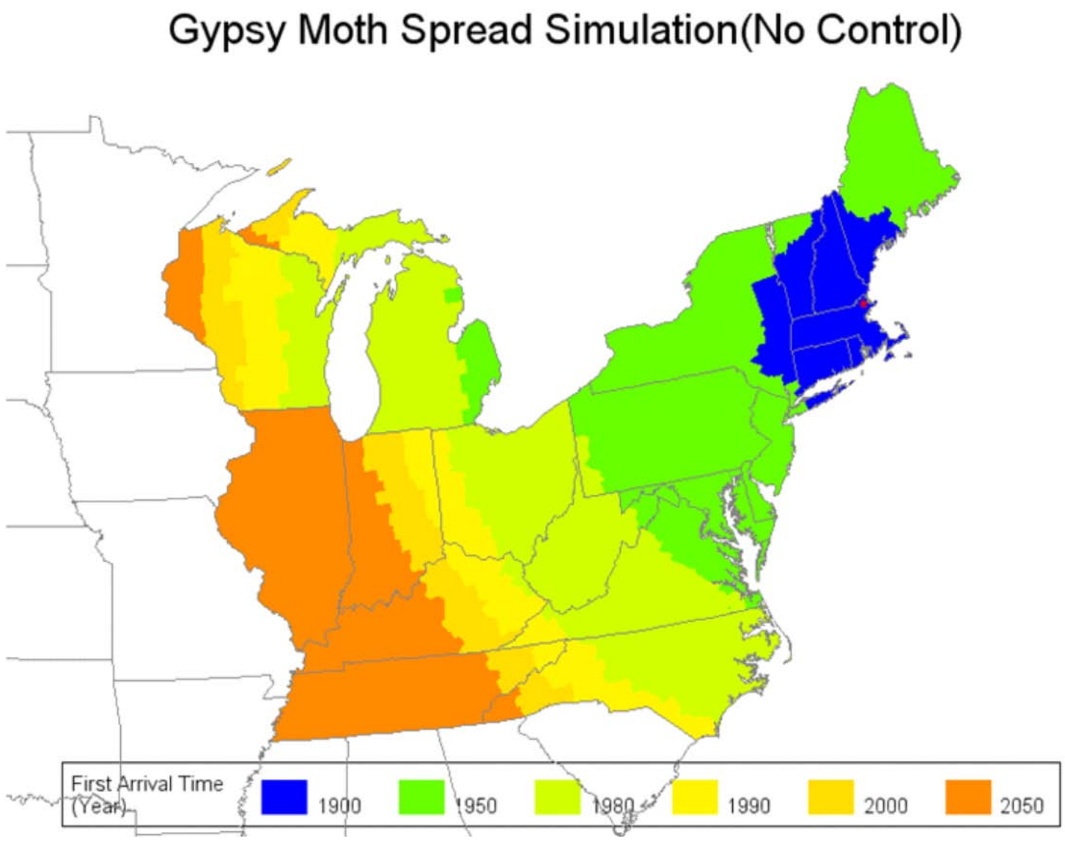


Figure 5.1 Gypsy Moth Spread Simulation (No Control)

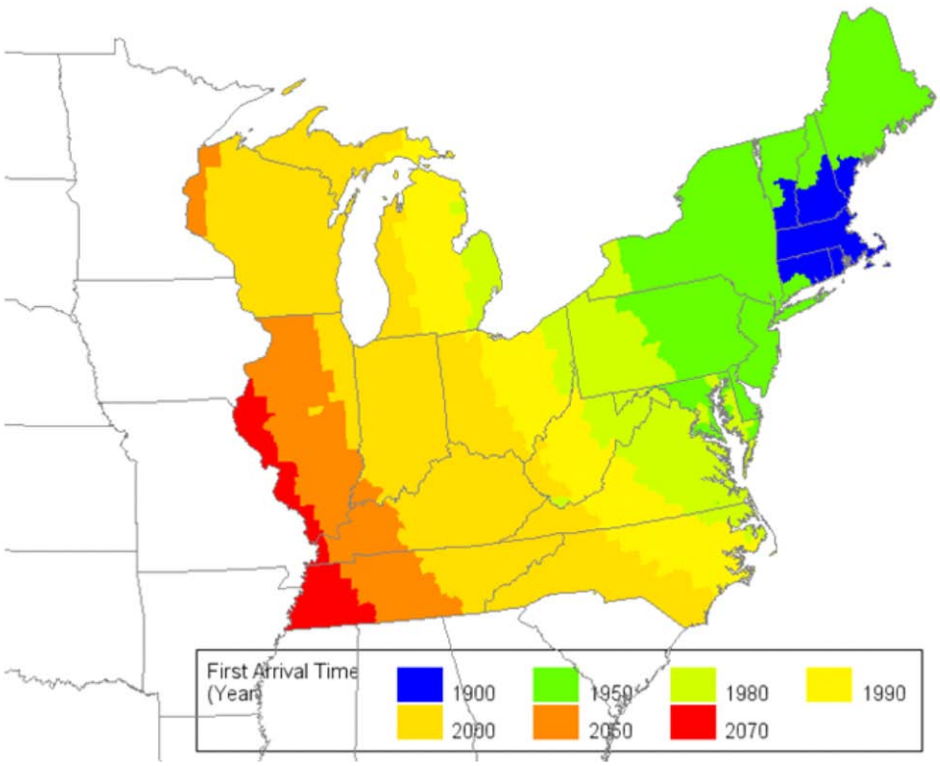


Figure 5.2 Gypsy Moth Spread Simulation (Spray Policy)

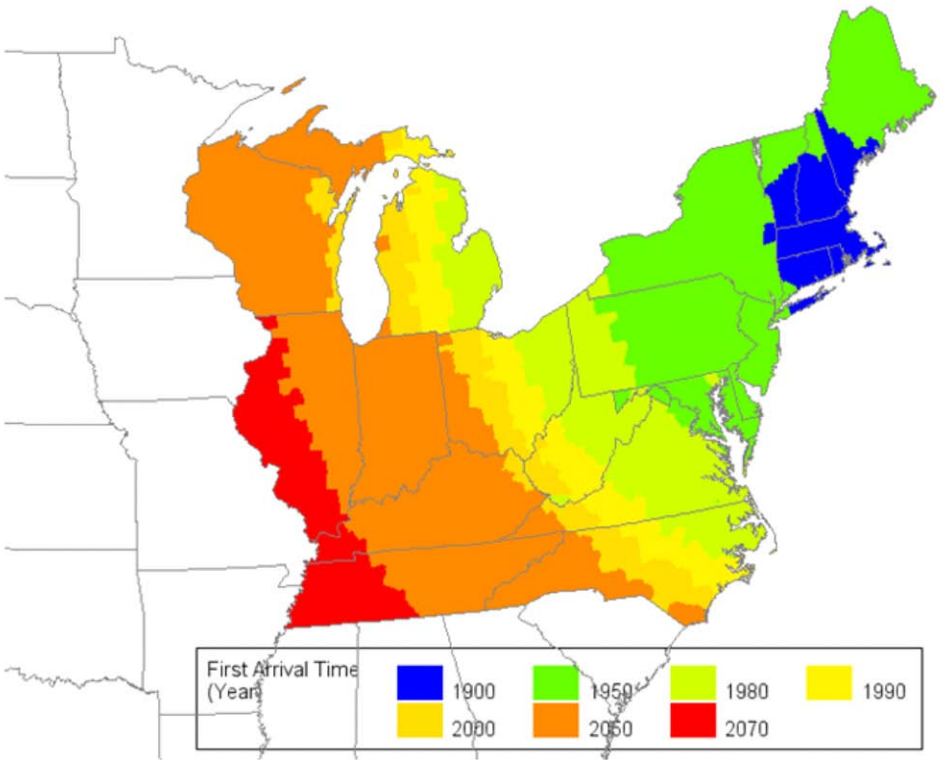


Figure 5.3 Gypsy Moth Spread Simulation (Quarantine Policy)

From the above graph, we can see the quarantine policy is more effective than the threshold policy in controlling the spread of gypsy moth.

Table 5.2 Summary Statistics for Different Control Scenarios

Scenarios	Damage+Cost (Unit: Million)	Reduction	Spread Rate	Reduction
No Control	$67.28	0	5.46mile/yr	0
Spray Policy	$59.60	11.41%	5.07mile/yr	7.14%
Quarantine Policy	$60.87	9.53%	4.83mile/yr	11.54%

We take “no control” as a benchmark. Compared to the “no control” case, the optimal spray policy will reduce the present damage and cost by 11.41% and slow the gypsy moth spread by 7.14%.Compared to the “no control” case, the quarantine policy will decrease the present damage and cost by 9.53% and slow the gypsy moth spread by 11.54%

5.4 Conclusions

The control of invasive species diffusion is an emerging problem confronting a lot of policy makers. We present a spatial dynamic model in this paper to discuss the structure of diffusion and evaluate possible control scenarios.

In this paper, I use the gypsy moth as an example to illustrate the optimal spatial management of invasive species, but the analysis can also be applied to other invasive species management. I develop a bioeconomic model and employ it to estimate the benefits from controlling the spread of an invasive species.

In the bioeconomic model, efforts to slow the spread will reduce diffusion rates, but at the same time, cost occurs. Slowing the spread will postpone and therefore reduce the sum of present value of damages and control costs. We evaluated spray strategy and quarantine strategy and compare them with no control case. We found that spray strategy is more effective in terms of reducing the total damage and cost. But the quarantine policy is more effective in controlling the front of the gypsy moth invasion.

This paper addresses the invasive species control question using a spatial dynamic model. It is valuable to extend the model to a smaller spatial scale. Since most gypsy moth management decisions are made at the stand level (10-100ha), higher resolution models would be more useful for management purposes.

Another possible extension of this model is the incorporation of different life stages and researchers can better analyze the damage and inform policy. Policy maker can target specific life stages and use different policies.

REFERENCES

[1] Andow, D. A., Kareiva, P. M., Levin, S. A., Okubo, A. 1990 Spread of Invading Organisms *Land Ecology* 4:177-188

[2] Bellman, R. 1957 Dynamic Programming Princeton University Press, Princeton, New Jersey

[3] Bjørnstad, O. N., Robinet, C., and A. M. Liebhold. 2008 Geographic Variation in the North American Gypsy Moth Population Cycles: Subharmonics, Generalist Predators, and Spatial Coupling Working Paper, Version 27-1, 39 pages

[4] Brock, W. and Xepapadeas, A. 2008 Diffusion-induced Instability and Pattern Formation in Infinite Horizon Recursive Optimal Control *Journal of Economic Dynamics and Control* 32: 2745-2787

[5] Brock, W. and Xepapadeas, A. 2010 Pattern Formation, Spatial Externalities and Regulation in Coupled Economic-ecological Systems Journal of Environmental Economics and Management 59:149-164

[6] Cliff, A. D. and Ord, J. K. 1981 Spatial Processes: Models and Applications Taylor and Francis

[7] Costello, C. and Polasky, S. 2008 Optimal Harvesting of Stochastic Spatial Resources *Journal of Environmental Economics and Management* 56: 1-18

[8] Eiswerth, M. E. and Kooten, G. C. 2002 Uncertainty, Economics and the Spread of an Invasive Plant Species *American Journal of Agricultural Economics* 84: 1317-1322

[9] Fisher, R. A. 1937 The Wave of Advance of Advantageous Genes *Annals of Eugenics* 7: 355-369

[10] Gottschalk, K. W. 1993 Silvicultural Guidelines for Forest Stands Threatened by the Gypsy Moth USDA Forest Service NE Forest Experiment Station General Technical Report NE-171

[11] Johnson, D. M., Liebhold, A. M., Tobin, P. C., and O. N. Bjørnstad. 2006. Allee Effects and the Pulsed Invasion by the Gypsy Moth *Nature* 444:361-363

[12] Lenhart, S. M. and Bhat, M. G. 1992 Application of a Distributed Parameter Control Modelin Wildlife Damage Management *Mathematical Models and Methods in Applied Sciences* 4:423-439

[13] Marsula, R. and Wissel, C. 1994 Insect Pest Control by a Spatial Barrier *Ecological Modelling* 75/76: 203-211

[14] Mollison, D. 1977 Spatial Contact Models for Ecological and Epidemic Spread *Journal of the Royal Statistical Society* B39: 283-353

[15] Sanchirico, J. N. and Wilen, J. E. 1999 Bioeconomics of Spatial Exploitation in a Patchy Environment *Journal of Environmental Economics and Management* 37:129-150

[16] Sanchirico, J. N. and Wilen, J. E. 2005 Optimal Spatial Management of Renewable Resources: Matching Policy Scope to Ecosystem Scale *Journal of Environmental Economics and Management* 50: 23-46

[17] Sanchirico, J. N., Albers, H. J., Fischer, C. And Coleman, C. 2010 Spatial Management of Invasive Species: Pathways and Policy Options *Environmental and Resource Economics* 45: 517-535

[18] Saphores, J. D. M. and Shogren, J. F. 2005 Managing Exotic Pests under Uncertainty:Optimal Control Action and Bioeconomic Investigations. *Ecological Economics* 52: 327-339

[19] Sharov, A. and Liebhold, A. 1998 Bioeconomics of Managing the Spread of Exotic Pests with Barrier Zones *Ecological Applications* 8:833-845

[20] Shigesada, N., Kawasaki, K. 1997 Biological Invasions: Theory and Practice New York Oxford University Press

[21] Skellam, J. G. 1951 Random Dispersal in Theoretical Populations *Biometrika* 38:

196-218

[22] Smith, M. D. and Wilen, J. E. 2003 Economic Impacts of Marine Reserves: The Importance of Spatial Behavior *Journal ofEnvironmental Economics and Management* 46:183-206

[23] Smith, M. D., Sanchirico, J. N. and Wilen, J. E. 2009 The Economics of Spatial-dynamic Processes: Application to Renewable Resources *Journal of Environmental Economics and Management* 57: 104-121

[24] Taylor, C. R. and Burt, O. R. 1984 Near-optimal Management Strategies for Controlling Wild Oats in Spring Wheat *American Journal of Agricultural Economics* 66: 50-60

[25] Wu, J. 2001 Optimal Weed Control under Static and Dynamic Decision Rules *Agricultural Economics* 25: 119-130

APPENDIX

Table A.1 Suppression Cost Summary Statistics

Year	Federal Share (Dollars)	State Share (Dollars)	Total Cost (Dollars)	Total Area Suppressed (Acres)	Average Cost ($/Acres)
1980	687,348	735,047	1,422,395	80,294	17.71484
1981	2,148,919	2,496,918	4,645,837	350,120	13.26927
1982	2,351,860	7,364,851	9,716,711	726,730	13.37046
1983	3,643,818	4,622,743	8,266,561	598,660	13.80844
1984	2,489,667	3,763,310	6,252,977	512,205	12.20796
1985	2,446,004	3,396,931	5,842,935	519,787	11.24102
1986	3,029,617	4,170,887	7,200,504	589,231	12.22017
1987	4,517,183	5,190,846	9,708,029	698,425	13.89989
1988	6,880,686	4,619,609	11,500,295	749,528	15.34338
1989	5,308,835	5,246,749	10,555,584	797,836	13.23027
1990	10,929,352	11,575,830	22,505,182	1,518,857	14.81718
1991	8,783,481	9,865,198	18,648,679	1,103,516	16.89933
1992	7,128,257	7,296,575	14,424,832	960,776	15.01373
1993	6,083,827	6,474,751	12,558,578	582,210	21.57053
1994	5,726,969	5,974,326	11,701,295	618,845	18.90828
1995	3,675,139	3,657,543	7,332,682	435,584	16.83414
1996	3,380,266	3,951,577	7,331,843	313,693	23.37267
1997	2,228,031	2,649,055	4,877,086	67,517	72.23493
1998	2,238,464	2,832,835	5,071,299	96,565	52.51695
1999	312,500	900,817	1,213,317	160,779	7.546489
2000	3,996,244	4,693,685	8,689,929	251,660	34.53043
2001	5,900,698	6,225,551	12,126,249	464,121	26.12734
2002	5,137,622	4,882,788	10,020,410	286,167	35.01595
2003	2,840,524	2,769,584	5,610,108	103,034	54.44909
2004	1,467,582	1,571,009	3,038,591	79,571	38.18717
2005	514,075	574,790	1,088,865	7,292	149.3232
2006	2,561,370	4,121,021	6,682,391	163,655	40.83218
2007	3,651,661	5,209,968	8,861,629	191,700	46.22655
Total	110,059,999	126,834,794	236,894,793	13,028,358	18.18301

Source: Gypsy Moth Digest, Morgantown, WV.

Table A.2 Calculation of Damage Function

	A	B	C	D	E	F
1	theta=	0.02331				
2	Defoliation Level	WTP	Diff	Data	Diff-Data	(Diff-Data) ^{2}
3	0	0				
4	10	2.33077				
5	20	9.32307	6.9923	2.969	4.0233	16.18694
6	30	20.9769	18.64613	8.676	9.970133	99.40355
7	40	37.2923	34.9615	42.001	-7.0395	49.55458
8	50	58.2692	55.9384	55.365	0.573398	0.328785
9						165.4738

The steps to calculate the optimal theta value are listed follows:

1) Set the initial value of θ (Cell B1), I use 0.001 as the initial value.
2) Calculate WTP as θx^2, where x is the defoliation level.

   (e.g. $B3=$B$1*$A3^2)

3) The Diff is the difference of WTP which is calculated as the WTP at specified defoliation level minus the WTP at 10% level.

   (e.g. $C5=$B5-B4)

4) Data is the value we derived from the survey.

5) Calculate the difference between Diff and Data

   (e.g. $E5=$C5-$D5)

6) And then square it

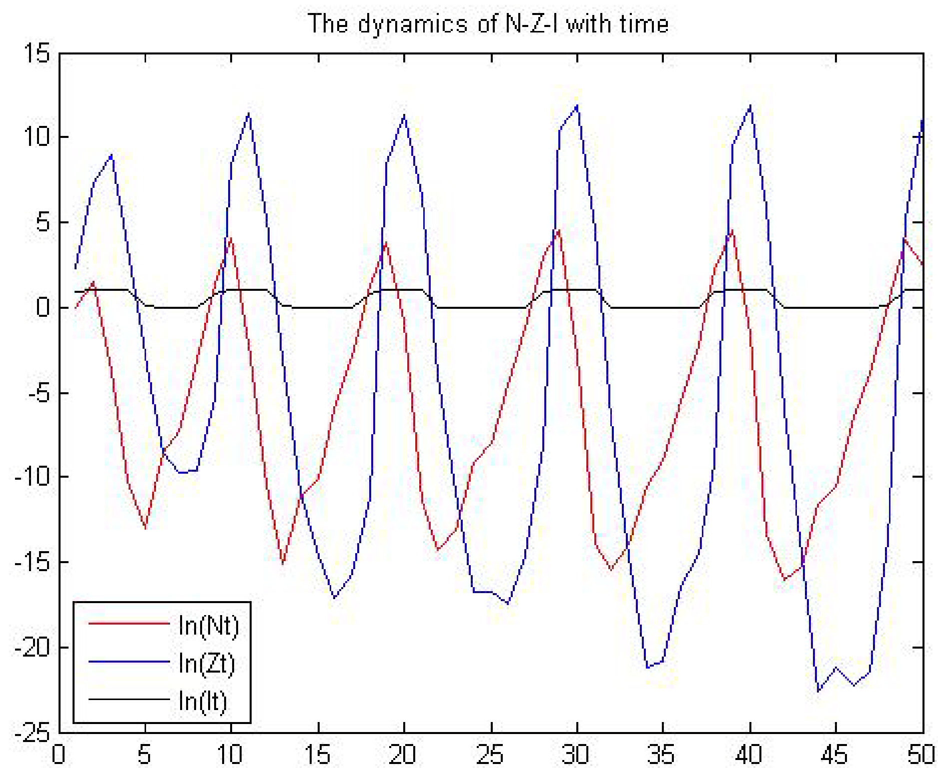
   (e.g. $F5=$E5^2)

7) Derive the sum of squared error

   (e.g. $F9=sum($F5:$F8))

8) Go to Excel solver and set target cell F9 equal to value of 0 by changing cells B1, the calculated theta equals 0.2331

Figure A.1 The Dynamics of N-I-Z system for the First Fifty Years



Survey Form for Determining Economic Damage of Gypsy Moth

This introduction provides a brief history and description of the gypsy moth in North America. It is followed by a survey to determine the willingness to pay by your household to reduce defoliation caused by gypsy moth caterpillars. The willingness to pay questions, at the end of the survey, will allow us to estimate the value of programs which might reduce the size of the gypsy moth population during an outbreak as well as the value of slowing its spread to Midwestern and Southern States. Please answer all questions to the best of your ability. Information about your household and its willingness to pay for gypsy moth control will be kept strictly confidential by Cornell University. Only the statistical results of all survey respondents will be shared with agencies in the towns, cities, states, and federal government who are responsible for managing the gypsy moth and other invasive species.

Background Information

The gypsy moth, Lymantria dispar, is a moth in the family Lymantriidae of Eurasian origin. Originally ranging from Europe to Asia, it was introduced to North America in the late 1860s and has been expanding its range ever since.

The gypsy moth has one generation per year. Each generation goes through four stages: egg, larva (caterpillar), pupal and adult stages.

Female moths lay egg masses on tree boles, branches, houses, vehicles, and other transportable objects. This aids their spread to new areas. Egg masses are buff-colored after they are initially deposited in late summer, but they become lighter in color as they bleach in the sun. Eggs that survive the winter hatch from early spring through mid-May.

Caterpillars have five double rows of dark blue spots, followed by six double rows of brick red spots on their dorsal surface. They also have a thin yellow median stripe along the length of their back.

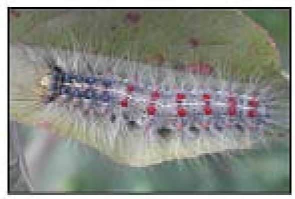
Mature caterpillars pupate from mid June through early July. Females are generally light tan with brown or dark tan bars on their wings. Female Gypsy Moths do not fly.

Gypsy moth caterpillars feed on tree leaves, affecting the tree's ability to photosynthesize. A single defoliation will not kill a tree unless the tree is already under stress. Trees impacted by the caterpillars will most likely push out a new set of leaves in several weeks. Two or three years of defoliation in a row will severely impact a tree, causing dieback and increasing its susceptibility to root diseases and attack by other insects.

There are many similar looking caterpillar species including the eastern tent caterpillar and the gypsy moth.The eastern tent caterpillar can be identified by the presence of a "white stripe" in place of the "footprint-shaped" marks. Gypsy moth can be recognized by its' paired red and blue spots.

FOREST TENT CATERPILLAR LARVA

EASTERN TENT CATERPILLAR



GYPSY MOTH

It is NOT a Gypsy Moth if it's:

• Building a cottony nest or web in trees

• A white moth that flies

• Larger than a 50 cent piece and colorful

• A caterpillar with long stripes on its back or sides

• Flying in the springtime

Information on Property in Question:

If you own two or more properties, please answer the following questions about the property designated as your primary (or legal) residence, hereafter referred to as "the property in question."

1. Location of Property:

______________Address

______________Zip Code

______________State

______________County

______________Town (if appropriate)

2. Would you classify the property in question as

____Urban,

____Suburban,

____Rural

9. How large is the property in question?

____acres

10. How long have you or your family owned the property in question?

____years

11. Approximate number of trees on the property in question?

____Number

12. Types of trees present on property (check all that apply):

____Deciduous (eg. oak, maple, hickory, beach, locust)

____Coniferous (pines, spruce, hemlock)

13. Do you harvest timber or firewood from the property in question on a regular

basis?

___Yes

___No

14. If the parcel in question is greater than five acres in size and located in a rural or suburban area, what are your land management objectives? (You may choose more than one)

____Timber and firewood

____Wildlife management, hunting

____Wildlife management, observation

____Recreation/aesthetics

____Water protection

____Soil conservation

____Other (Please specify)__________________

Experience with Gypsy Moth Outbreaks

15. Have you ever noticed Gypsy Moth caterpillars on the trees on the property in question?

__Yes

__No

16. If you answered "Yes", do you recall the year of the most recent Gypsy Moth outbreak?

____year

17. In your opinion, how serious was the Gypsy Moth outbreak in that year?

___Very serious

___Somewhat serious

___Not serious

18. Of the various negative impacts caused by the Gypsy Moth catterpillar, please rank the following in order of concern, where 1=of most concern, 2=of next most concern, 3=of least concern.

___Risk of Tree Mortality,

___Dimenished Enjoyment of Outdoor Recreation,

___Visual Impact of Defoliated Trees

19. Has the property in question experienced defoliation caused by Gypsy Moth in the past 30 years?

___Yes

___No

20. If you answered "Yes", the defoliation can be described as:

___Light

___Moderate

___Heavy

(Note: Lights means less than 30% defoliation, moderate means 30% to 60% defoliation, heavy means greater than 60% defoliation.)

21. In your assessment, did Gypsy Moth defoliation cause tree mortality on your property?

___Yes

___No

22. Have you taken any actions to control Gypsy Moth caterpillars?

___Yes

___No

23. If you answered "Yes", what kind of actions did you take?

___Mass trap

___Mating disruption

___Btk (Bacillus thuringiensis kurstaki)

___Spraying pesticide

___Other (Please specify)

24. How much money did you spend controlling Gypsy Moth caterpillars during the most recent outbreak?

___Under $500

___$500-$999

___$1000-$1999

___$2000-$2999

___$3000-$3999

___$4000-$4999

___Over $5000

25. In the time you have lived at the property in question, have you observed more than one Gypsy Moth outbreak?

___Yes

___No

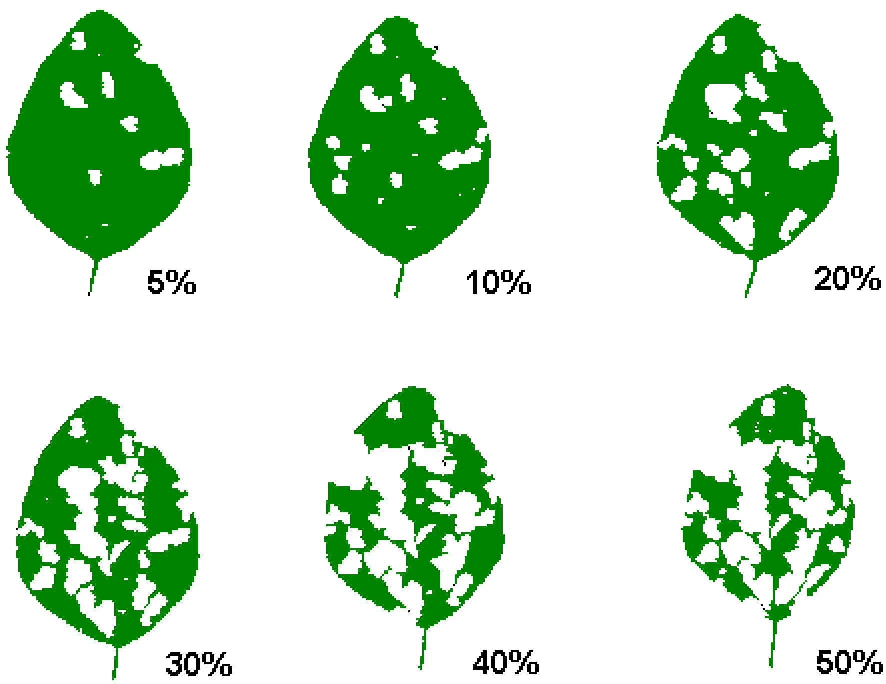
26. If you have experienced more that one Gypsy Moth outbreak do you remember the outbreak years?

____Year of Previous Outbreak

____Year of Next Previous Outbreak

Willingness to pay to avoid the defoliation

The above leaves demonstrate light, moderate and heavy defoliation caused by Gypsy Moth.



27. Suppose you are a member of a local woodland owners association that is trying to control the Gypsy Moth in your area. Would you be willing to pay $50, per acre, per year, to reduce defoliation from 20% to 10% as indicated by the leaves shown above?

___Yes ___No

28. If you answered "Yes" in question 27, would you like to pay $100, per acre per year, to reduce defoliation from 20% to 10% as indicated by the leaves shown above?

___Yes ___No

29. If you answered "No" in question 27, would you like to pay $25, per acre per year, to reduce defoliation from 20% to 10% as indicated by the leaves shown above?

___Yes ___No

Background Information on Respondent and Respondent's Household:

1. Respondent's Password:________________

2. Respondent's Name:___________________

3. Sex: ___Male, ___Female

4. Highest Educational Degree (check one): ___None, ___High School,

___Two-Year College

___Four-Year College/University, ___Post Graduate Degree

5. Approximate Annual income of your Household:

___Under $20,000

___$20,000 - $29,999

___$30,000 - $39,999

___$40,000 - $49,999

___$50,000 - $59,999

___$60,000 - $69,999

___$70,000 - $79,999

___$80,000 - $89,999

___$90,000 - $99,999

___$100,000 - $149,999

___$150,000 - $249,999

___$250,000 - $499,999

___$500,000 and over

6 How many people live in your household (including students not in residence)?

___Adults (≥21)

___Juveniles (13 through 20)

___Children (≤12)